The Zen of IRAF

A Spiritual User's Guide to the "Image Reduction and Analysis Facility" for the LINUX Novice

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I. INTRODUCTION

Go beyond this way or that way, to the farther shore where the world dissolves
and everything becomes clear. Beyond this shore and the farther shore,
Beyond the beyond, where there is no beginning, no end, without fear, go.

- Buddha in the Dhammapada

"IRAF is the Image Reduction and Analysis Facility, a general purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation" (from http://iraf.noao.edu/iraf/web/).

The astute reader will have already noticed that IRAF is made by a consortium, controlled by a government contractor, overseen by a committee. That's the bad news. The good news is that IRAF is the most powerful, free, software for CCD image reduction and analysis that the U.S. taxpayer ever provided the astronomical community, amateur and professional alike. That said, it has also been called one of the most "user-antagonistic" pieces of software ever written (Hager, 2002). Part of this fact is that it is primarily command line driven; remember MS-DOS? Another fact is that editing text files does configuration of tasks, not using nifty dialogs as in Windows. But, once the user gets into the method behind the madness, the logic behind IRAF can begin to grow on one.

IRAF is extremely well documented, with both on-board help files for every task as well as a number of web accessible tutorials, reference guides, and user manuals (see resources). That's the good news. The bad news is that the documentation has not kept up with version revisions. So, while you can get from A to B following examples in the help files and other documentation, you probably worked too hard to get there. The most glaring example of this problem is that, originally, IRAF required that FITS format images be converted into an IRAF native format, .imh, using the command "rfits". This step, and references to .imh files, fills the documentation. Yet, starting around 1995, IRAF became able to handle FITS files transparently, with no need for image conversion! This document will try to help you avoid the painful steps to IRAF self-realization the author endured.

Originally intended for UNIX mainframes with tape drives, IRAF has been made accessible to the LINUX PC's that are replacing even Sun workstations. This conversion again comes with a price - the documentation is not specific to the LINUX version, and may even conflict at times. One personality trait of LINUX users is (or should be) that they are willing to exchange thinking by droids in Redmond, Washington (Microsoft) with greater computing power at the expense of complexity. The user who sees every error message, failure to execute a command, or system lock up as a worthy challenge, will do well with LINUX and IRAF. The user who doesn't will likely be found naked, screaming, in the rain, on a dark night, in their local city park prior to being institutionalized. Or follow the legions of previous users who just gave up trying. Be of stout heart! IRAF's ability to simplify, yes simplify, your image reduction and photometry is worth the journey; as is the benefit to your personal spiritual growth though adversity. And you *will* grow...

II. BEGINNINGS

One equal temper of heroic hearts,
Made weak by time and fate, but strong in will
To strive, to seek, to find, and not to yield.

- Tennyson

A. Background

As part of Swinburne Astronomy Online, I chose to do a project in HET611 –- astrophysics, involving plotting and interpreting a Color-Magnitude Diagram (CMD) for the open cluster M67. I decided to combine aspects of this project with another course taken concurrently, HET609 - Imaging. So, for the imaging project (this document) it was proposed to make a user's guide to IRAF. Specifically, this guide was to be for the non-LINUX expert and would also be more current than the official offerings from NOAO. The author had dabbled with IRAF in the past, but knew that the need to make a class deliverable would be an incentive to really "break though" past failures and disappointments. The CMD project involved the calibration of B, R, and I images of SA104, SA107 (each at several airmasses) and M67 taken with a 2085 by 2085 pixel CCD at McDonald Observatory by PhD candidate (now Dr.) Pamela Gay. The student was expected to process the data fully, though a B-R vs R plot on the Johnson-Cousins UBVRI system.

B. Assumptions

It is assumed you have an i86 PC clone, with some flavor of LINUX installed and working. The project was performed using Red Hat 7.2, on a Pentium -4 clone with 256MB of RAM, and an 80 GB hard drive. If you don't have this horsepower, some of the image processing steps will just take a bit longer. "NOAO PC-IRAF Revision 2.11.3 EXPORT Thu Feb 10 23:10:10 MST 2000" (from the "Welcome to IRAF" paragraph that shows every time you start IRAF) was used. As of this writing, they are up to PC-IRAF 2.12.1, but it is assumed that there are no significant differences at the level we will be working. Aa KDE Graphical User Interface (GUI) was used, but GNOME would work just as well. It is also assumed you have downloaded and installed SAOIMAGE - DS9 as an image viewer. (see the resources section). But, you can use the integral IRAF viewer (XIMTOOL) if you wish, (see below).

C. LINUX Review

LINUX is a powerful, multitasking operating system for i86-based PCs, developed by Linus Torvalds in 1991. At the command line, it is at heart UNIX, which has existed in various forms since the days of punch cards. Unlike Windows, LINUX does many operations at once, and is nearly immune to system crashes (e.g. the infamous Microsoft "blue screen of death"). However applications can and do crash on LINUX, as you'll see with IRAF. Various forms of LINUX can be downloaded free, and installed in conjunction with a Windows operating system such that you can choose at boot up which system you want to use. Or you can purchase some LINUX flavors, such as Red Hat, and get access to good manuals and even telephone technical support. If you are not really into computers, a good technical guide for your LINUX system is a must, because the onboard "man" (manual) pages are often too terse and too comprehensive for the non-technogeek. For RH 7.2, one such tome is the "Red Hat Linux 7.2 Bible-unlimited version" (Megus 2002 - Hungry Minds , Inc.) which is comprehensive yet

understandable. And, they include the three installation CD-ROMS as well, justifying the U.S.$50 price!

D. Installation of IRAF on the LINUX-PC

1.Where to get it.

Having heard horror stories about trying to install the ftp version, the author purchased "LINUX for Astronomy CD-ROM, Volumes 5 and 6" from "The Random Factory". They have compiled for LINUX a vast amount of professional astronomical software, and developed, where needed, install scripts to automate the installation. This approach was cheap (U.S.$80) and following the instructions was painless. You can also download it for free, and follow NOAO's instructions. It is rumored that the later versions of PC IRAF install much easier than the older versions. But, once installed, you still have a bit of configuration to do to make it work.

2. Setting up your basic parameters - login.cl

The file login.cl was placed in whatever directory you installed IRAF (probably your home directory, home/username) when you executed the 'mkiraf' command to finish installation. Using the command line command 'find login.cl' , (type without the quotes, and hit enter to input the command) should help you find it. Once found, lets first make a copy of the default file, just in case something bad happens. Use 'cp login.cl login.cl.bak' to make a copy. Now let's look at login.cl with your favorite text editor. This author prefers EMACS, so 'emacs login.cl' should bring it up. Note that any thing with a # in front of it in the login.cl file is not enabled.

Refer to the login.cl file, in the Appendix if you don't have one on the screen in front of you. 'set home' tells you where IRAF is. 'imdir' is where .imh pixel files are stored, but we won't be using them - just ignore it. Also ignore right now 'uparm' and 'useid'. Under set terminal type, you'll see some programming language, then 'stty gterm' and later 'stty xterm'. We'll open IRAF in an Xterm window manually, so just leave these alone. The next parameters are some important ones. 'Editor' is which LINUX text editor will be invoked by IRAF with the command 'edit'. To change from the default vi, just type over that with emacs, pico, or leave it at vi if you are comfortable with that editor. 'stdimage' is the default image size you will be using in terms of pixels. For most amateur CCD, the 'imt512' value is fine. But, for this project, 'stimage' was reset to 'imt2048' as the trimmed images were 2048 by 2048 pixels square. 'imtype' should tell the file extensions of your images; the author's were 'fit'. 'imextn' is an function that will allow IRAF to open various types of FITS extensions (like fit, fts, fits) that are used often interchangeably. The author' is set to 'imextn="fxf:fit,fts,fits oif:imh ', to cover all the bases. That's pretty much it at this point. Save your file and exit. You should be ready to go.

Note that if you want to try any change to login.cl without actually changing the file, you can always type one of the 'set" lines from the IRAF command prompt cl>. For example, you want to try using vi as a text editor type: 'set editor=vi' to change it for just that session.

E. Getting to know the Beast - Fun with dev$pix

1.Opening IRAF

Now comes the big moment, seeing if it will run. First open a terminal window (also called a shell). You should see something like: [cpullen@unit7 cpullen]$ if you are using BASH as a shell language. Now, let's open a Xterminal window: type 'xterm'. IRAF may not open from BASH, so change to CShell with the command "csh". You now will now see [cpullen@unit7 ~]# for a prompt, and note that the upper left corner of the window has X in it, not Konsole. Open IRAF with the command 'cl'. If all goes well, you'll see:

```
 NOAO PC-IRAF Revision 2.11.3 EXPORT Thu Feb 10 23:10:10 MST 2000
   This is the EXPORT version of PC-IRAF V2.11 supporting most PC systems.

   Welcome to IRAF.  To list the available commands, type ? or ??.  To get
   detailed information about a command, type `help command'.  To  run  a
   command  or  load  a  package,  type  its name.  Type  `bye' to exit a
   package, or `logout' to get out of the CL.  Type `news'  to  find  out
   what is new in the version of the system you are using.  The following
   commands or packages are currently defined:

     dataio.    images.    lists.     obsolete.  proto.     system.
     dbms.      language.  noao.      plot.      softools.  utilities.
cl>
```

Now, from the cl> prompt, let's open our image viewer, DS9, by typing '! ds9 &' . DS9 should open in a separate window. Yea! You are up and running.

Note that the way to close IRAF is to type 'logout' at the prompt. Just closing the window could leave it unhappy. Also, if you get any kind of error message, reset things with the command 'flpr' which is supposed to recover any faulty processing from the error. You'll want to do flpr if you ever use 'cntl-c' to abort an IRAF process that is running away or hung up.

2.Why DS9?

IRAF has an onboard image viewer included in the distribution, ximtool. Why not use that? The simple answer is that it only works if your computer is set up for 8-bit color. Most folks have not used 8-bit color since their first color Macintosh was purchased in 1985. 8 bit means 2^8 colors to represent every possible shade. That's 512 colors. Your computer is probably running 16 or 24-bit color. DS9 will run fine on either of those. Or, if you want to use ximtool, change your color scheme by typing 'xconfigurator' at the shell command line, and follow the instructions (select with the space bar, move though the menus with the tab key). If you only use the computer for IRAF, it probably won't matter changing it to 8 bit, but if you want to see photos of your grandchildren, you'll want to get DS9 so you don't have to keep changing back and forth, and rebooting each time you do.

3.Basic IRAF Tasks

a. Image Display

Let's open an onboard image: type 'display dev$pix 1'. The image of M51 should appear in DS9 frame

1 of 4. A little playing with DS9 is in order here; make sure you know how to toggle the various frame modes. You could have just typed the command 'display' and IRAF would have sequentially asked for the name of the image, then the frame as below.

```
cl> display
image to be displayed (104b2): dev$pix
frame to be written into (1:4) (1): 1
cl>
```

So, ‘display dev$pix 1’ just made things happen a bit quicker. This is a characteristic of all IRAF commands: You can use long and detailed commands, or be prompted in small chunks.

b. Changing the parameters of a command with parm files.

Now is as good a time as any to get into parm (parameter) files. Every IRAF command has a parm file that fixes the parameters for that command. When you are typing ‘display dev$pix 1’, or waiting for IRAF to prompt you, it is looking to see what is in that parm file for the display command. Let's look at the 'display' parm file with the command 'lpar display'.

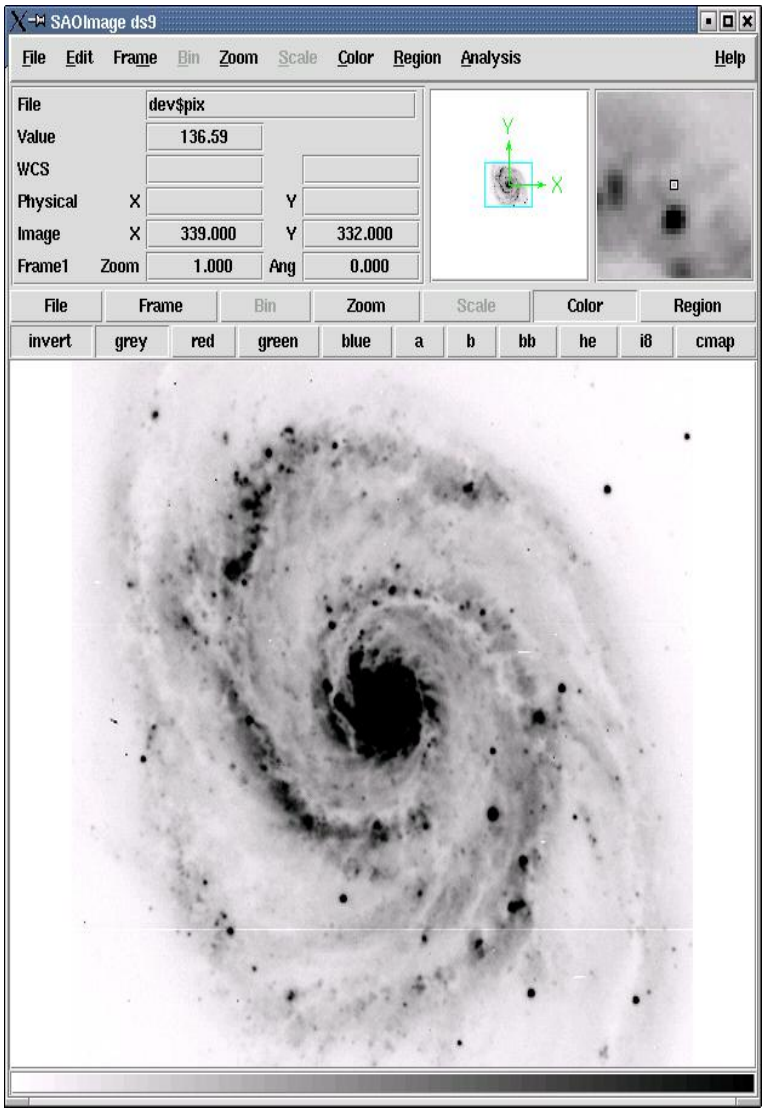


Figure 1 – dev$pix (negative view)

```
cl> lpar display
       image = "104b2"        image to be displayed
       frame = 1              frame to be written into
     (bpmask = "BPM")         bad pixel mask
   (bpdisplay = "none")       bad pixel display (none|overlay|interpolate)
    (bpcolors = "red")        bad pixel colors
     (overlay = "")           overlay mask
     (ocolors = "green")      overlay colors
      (erase = yes)           erase frame
(border_erase = no)           erase unfilled area of window
(select_frame = yes)          display frame being loaded
      (repeat = no)           repeat previous display parameters
       (fill = no)            scale image to fit display window
     (zscale = yes)           display range of greylevels near median
    (contrast = 0.25)         contrast adjustment for zscale algorithm
     (zrange = yes)           display full image intensity range
      (zmask = "")            sample mask
    (nsample = 1000)          maximum number of sample pixels to use
    (xcenter = 0.5)           display window horizontal center
    (ycenter = 0.5)           display window vertical center
```

```
      (xsize = 1.)          display window horizontal size
      (ysize = 1.)          display window vertical size
       (xmag = 1.)           display window horizontal magnification
       (ymag = 1.)           display window vertical magnification
      (order = 0)           spatial interpolator order (0=replicate, 1=line
        (z1 = )             minimum greylevel to be displayed
        (z2 = )             maximum greylevel to be displayed
    (ztrans = "linear")       greylevel transformation (linear|log|none|user)
   (lutfile = "")           file containing user defined look up table
      (mode = "ql")
cl>
```

The columns are "parameter="what's set", then a description of the parameter. Note that ‘image’ and ‘frame’ are not in parentheses. These have to be set each time the command is invoked. However, the parameters in parenthesis are generally not changed often.

You can modify the parm file with the command ‘epar display’. Your cursor can be navigated up and down the options with the up and down arrow keys. To change a parameter, just type over it, then hit enter. Make a mistake while typing and you can’t backspace because of some incompatibility with your system? Save it with ‘enter’ then retype it. When done, move the cursor to the last line of the file (mode) and exit and save the parm file with ':q'.

Try changing the display parm file to display dev$pix in frame 4, then quit and save. Now, at the cl> type display, then hit the return key to accept the offered value in parentheses as below.

```
cl> display
image to be displayed (dev$pix): [return]
frame to be written into (1:4) (4): [return]
cl>
```

Toggle DS9 into frame - tile mode, and you should see two panes of the M51 image. You'll become familiar with parm files as we go ahead, but to recap:

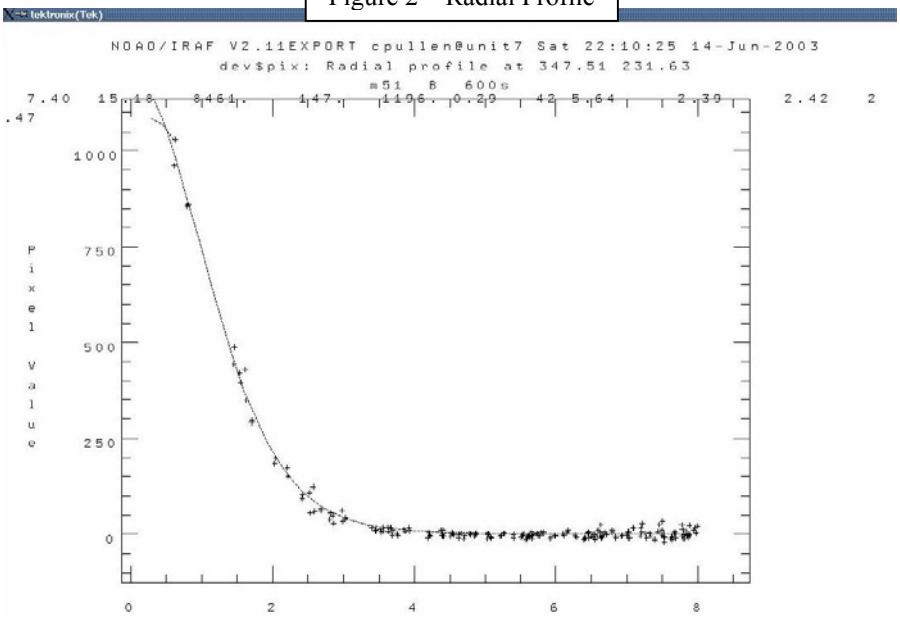
- Every command has a parameter file.
- You can look at the file by the 'lpar' command, and edit the file with 'epar' command.
- The top items in the file without parenthesis are mandatory, they either have to be in the parm file, or put there from the command line when the command is invoked.
- You can exit editing by moving the cursor to the bottom and typing :q

What if you think you have somehow damaged the parm file for a given command? Type: 'unlearn command'. That returns the parm file to the default value.

While at ‘display’, we also should learn about help pages for every command. The help file covers all the gory details, including some examples of how to use a given command. Type 'help display', and you'll get a detailed explanation of every one of those "hidden parameters", and more information. Scroll one page at time with the space bar. At the end, quit with 'q' or by scrolling down past the bottom of the file. But note – the help files are not necessarily current! In addition, they are not specific to the LINUX version. As one example, they will be full of references to those .imh images you no longer need! *Part of the Zen of IRAF is learning to remain calm and centered in the face of non-current instructions.*

c. ‘imexamine’

Figure 2 – Radial Profile



Now that we have an image, lets use the powerful IRAF tool 'imexamine'. First, lets look at the parm file to see what set up is needed, 'lpar imexamine'. Then, to learn more about imexamine by reading the help file, do 'help imexamine'. What's the difference between input and image in the essential parameters? What does imexamine do?

Let’s try it on our dev$pix image. With the image displayed, just type 'imexamine'. Note that the IRAF command line cursor changes appearance, and the cursor on DS9 changes to a round flashing circle. Moving that cursor with a mouse, you can get a variety of data off the image. type ‘?’ and you'll get a list of cursor commands, such as:

CURSOR KEY COMMAND SUMMARY

? Help	g Graphics cursor	n Next frame	u Vector plot
a Aperture Sum	h Histogram	o Overplot	v Vector plot
b Box coords	i Image cursor	p Previous frame	w Toggle logfile
c Column plot	j Line gaussian fit	q Quit	x Coordinates
d Load display	k Col gaussian fit	r Radial plot	y Set origin
e Contour plot	l Line plot	s Surface plot	z Print grid
f Redraw	m Statistics	, Quick phot	. Quick profile fit

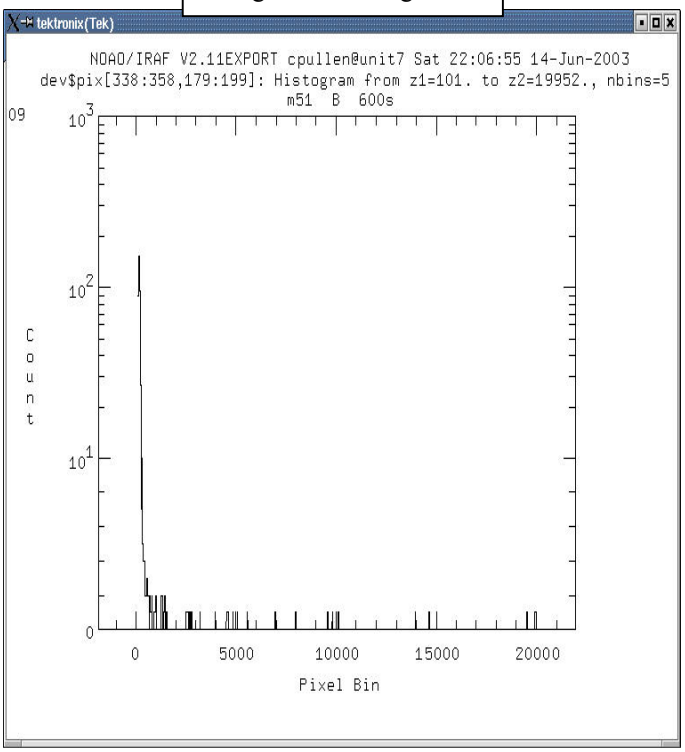
Place the cursor over a bright star on dev$pix, then type 'r'. A radial plot should pop up showing you the FWHM of the image (the 2.5 numbers to the right. Don't close the popup yet, or you'll crash IRAF. Move the cursor to another bright star, and hit 'c' for a contour plot. Try 'h' for a histogram. On the same star, try 'a' for aperture photometry. Now you'll get a print out to your IRAF text window with data like:

```
#   COL    LINE   COORDINATES
#    R   MAG    FLUX    SKY    PEAK    E   PA BETA ENCLOSED   MOFFAT DIRECT
 441.96  409.67 441.96 409.67
        13.93  26734.     45.   3279. 0.02  -57 5.41     2.34     2.43   2.38
```

Also try '.' and ',' for photometry. You get similar information, but you may prefer one way over another. Now, try 'x' for coordinates, and get something like: 478.00 329.00 49 where you have the X pixel, Y pixel, and the value of the pixel. Try both 'a' and 'x' on the same star, and see if the pixel coordinates match. The 'a' coordinates are based on a centroid solution. Exit imexamine with a 'q'. Then close the graphics window.

Congratulations, you have gotten things working in IRAF, opened an image, extracted information from it, and learned how to access set up (parm) files and modify them. If you feel karmic distress at this point, stop for a time to re-center yourself, perhaps helped by some time in a hot tub, or your favorite recreational beverage.

Figure 3 - Histogram



III. IMAGE CALIBRATION

If you want to know the realm of buddhahood, you must make your mind as clear as empty space.Leave false thinking and all grasping far behind ,causing your mind to be unobstructed wherever it may turn. The realm of buddhahood is not some external world where there is a formal "Buddha." It's the realm of the wisdom of a self-awakened sage.

Zen Master Ta-hui (1088-1163)

If you just asked yourself, "What's image calibration?" please stop (now!) and look at some of the links on basic CCD image theory and practice. However, if words like "bias" and "twilight flats" mean more than referring to how referees treat your favorite sports team, and a case of beer on the beach at sunset, respectively, then read on and be awed at the power of IRAF.

A. Overview

In this section we'll learn how to sequentially:

- Tell IRAF what kind of image is what
- Fix bad pixels and rows (if present) with a badpixel mask
- Read the bias strip and do an initial bias subtraction
- Trim unwanted portions of the image
- Make a median combined master bias image, and apply it to our image set
- Make median combined master flats for each filter, and apply it to our image set.
- Register images of the same field so that the stars are at the same coordinates

We'll be using mostly 'ccdproc' for this work, although (like the rest of IRAF) there are several other ways to do it. The advantage of 'ccdproc' is that you can do a full night's image calibration with a very few instructions once it is set up and you understand what you are doing.

B. File Names

IRAF can make powerful use of the "*" wild card function if you set up your image file names right. It can also use image lists as inputs into calibration commands, where by you listed the names of the

file you wanted processed - once - into a text file. However, I find that image names that tell me what the image is, and what kind of image it is are very time saving. I use the following conventions:

Flats: flatFN.fit (example: flatR1.fit)
Bias: zeroN.fit (example: zero5.fit)
Fields: "field"FN.fit (example: M67B3.fit)

where:

F = filter name (BVRI)
N= frame number (1,2,3...N)
"field"= field name (M67, SA104, SSCyg)

Another thing to keep in mind is that when running image calibration routines though the ccdproc command, IRAF will sort out which files are which from the image header. But it sure helps if you can tell what an image is up front. Something like "sci0001tr5.fit" is a bit cryptic.

C. Getting Headers Straight

Because IRAF will be using image headers, they need to be right. You can get a short-listing of what is in a given directory by using the "imheader *.fit" command. With my project, you get the following partial output:

```
cl> imheader *.fit
104b1.fit[2080,2048][ushort]: SA104 B
104b2.fit[2080,2048][ushort]: SA104 B
104i1.fit[2080,2048][ushort]: SA104 I

...
```

Deciphering, you have:

image name [Number of X pixels, number of Y pixels][image type]:Name on header

1. Subsets

It is important that the image headers tell IRAF the information that is needed. One way to do this, if it isn't done as part of the image acquisition process, is to explicitly tell IRAF what is what in an image set. You can use your file name conventions to help with this task. Use the 'ccdedit' task in the ccdred package:

```
cl> ccdedit
ERROR: task `ccdedit' not found
cl>
```

What! *Remember that peace is in the mind of the believer- believe you are at peace, and you will be at peace…*

IRAF loads a small set of tasks at start up. You can modify that list, it's in your login.cl file. But remember that IRAF was written in the days of limited memory. So, we have to load the package that ccdproc is in. That is done as follows:

Change to 'noao'

```
cl> noao
    artdata.    digiphot.    mtlocal.    observatory   surfphot.
    astrometry. focas.       nobsolete.  onedspec.     twodspec.
    astutil.    imred.       nproto.     rv.
```

Change to 'imred'

```
no> imred
    argus.    ctioslit.  generic.   irred.    kpnoslit.
    bias.     dtoi.      hydra.     irs.      specred.
    ccdred.   echelle.   iids.      kpnocoude. vtel.
```

Change to 'ccdred'

```
im> ccdred
    badpiximage     ccdmask         darkcombine     mkskycor
    ccdgroups       ccdproc         flatcombine     mkskyflat
    ccdhedit        ccdtest         mkfringecor     setinstrument
    ccdinstrument   combine         mkillumcor      zerocombine
    ccdlist         cosmicrays      mkillumflat
cc>
```

I asked for the 'noao' package, which gave me another list. I asked for the 'imred' package, and finally the 'ccdred' package that has 'ccdedit' in it. Note that the prompt changed each time I switched packages (cl> to no> to im> to cc>). That is one way IRAF tells you where you are. To go back (or unload) a package, type 'bye':

```
cc> bye
    argus.    ctioslit.  generic.   irred.    kpnoslit.
    bias.     dtoi.      hydra.     irs.      specred.
    ccdred.   echelle.   iids.      kpnocoude. vtel.
Im>
```

See how I moved back one step? So, to get back all the way to the cl> prompt, I'd have to type 'bye' for each level. Yes, there are layers and layers of packages, each with a number of different tasks. "In complexity one can find beauty".

To review, ccdhedit is in the ccdred package. To get there, you have to move as follows: opening level (cl>), noao (no>), imred (im>),ccdred (cc>). To move back in the package set, type 'bye' for each level.

Now, back to subsets. We want to teach IRAF what each type of image is. We are confirming the 'imtype' and are adding 'filter' to the image header. Here is how to do it with 'ccdhedit':

```
ccdhedit bias* imgetyp zero
ccdhedit flat* imagetyp flat
ccdhedit dark* imagetyp dark
ccdhedit flatB* subset "B"
ccdhedit flat R* subset "R"
ccdhedit flatI* subset "I"
ccdhedit field1!* imtyp object
ccdhedit field1B* subset "B"
ccdhedit field1R* subset "R"
```

```
ccdhedit field1I * subset "I"
ccdhedit field2* imtype object
ccdhedit field2*B subset "B"
(repeat as for field1 to field n)
```

Now, if this seems like a lot of typing, it is. If you can set up your acquisition software to do it for your, so much the better. Or, if you use the same naming conventions all the time, you can make up a simple shell script (or an IRAF script) to type all this in for you. See the example of a script in the 'ccdhedit' help file.

2. Header Inspection

So, how did IRAF know what was what when I typed 'imheader'?

```
104b1.fit[2080,2048][ushort]: SA104 B
```

It got the information from the image header, either because the camera operating software put it there, or we later added it, or a combination of both.

If you want to look at the entire header, then type 'imheader m67r.fit l+' and your output will be:

```
m67r[2046,2046][real]: M67 R
No bad pixels, min=0., max=0. (old)
Line storage mode, physdim [2046,2046], length of user area 2673 s.u.
Created Sat 15:17:47 10-May-2003, Last modified Sat 15:17:44 10-May-2003
Pixel file "m67r.fit" [ok]
ORIGIN  = 'NOAO-IRAF FITS Image Kernel July 1999' / FITS file originator
EXTEND  =                    F / File may contain extensions
IRAF-TLM= '15:17:44 (10/05/2003)' / Time of last modification
OBJECT  = 'M67 R   '           /
DATE    = '2003-05-10T15:17:47'
IRAF-MAX=          5.683400E4  /  DATA MAX
IRAF-MIN=          3.187000E3  /  DATA MIN
OBSERVAT= 'MCDONALD         '  /  observatory
EXPTIME =               60.00  /  actual integration time
DARKTIME=               60.00  /  total elapsed time
IMAGETYP= 'object           '  /  object, dark, bias, etc.
DATE-OBS= '2001-04-24       '  /  date (yyyy-mm-dd) of obs.
UT      = ' 3:21:57.35'        /  universal time
ST      = '10:34:46.47'        /  sidereal time
EPOCH   =             2001.31  /  epoch of ra and dec
HA      = '+10:34:46.5      '  /  hour angle
ZD      = '21.27            '  /  zenith distance
AIRMASS =              1.073  /  airmass
TELESCOP= 'mcd30            '  /  telescope name
PROGRAM = 'ICE-1.5          '  /  program used to get and write data
DETECTOR= 'lf1_0004         '  /  detector microcode name
SSI     = '#5 Revision B    '  /  synchronous serial interface id
DSP     = '#6 Revision F    '  /  digital signal processor id
PREFLASH=                    0  /  preflash time, seconds
GAIN    =               1.60  /  gain, electrons per adu
RDNOISE =               5.87  /  read noise, electrons
CAMTEMP =                    0  /  camera temperature
DEWTEMP =                    0  /  dewar temperature
CCDSEC  = '[2:2047,2:2047]'    /  orientation to full frame
ORIGSEC = '[1:2048,1:2048]  '  /  original size full frame
CCDSUM  = '1 1              '  /  on chip summation
INSTRUME= 'pfc              '  /  instrument
```

```
INSFILTE= 'R               '  /  instrument filters
INSFOCUS= '-788            '  /  instrument focus
INSTRTEM= '  9.59          '  /  instrument current temperature
HISTORY 'KPNO-IRAF'          /
HISTORY '2001-04-26T09:11:56'
FILTERS = 'R      '
```

Some of the fields that were added or altered with our 'ccdhedit' exercise above have been highlighted. Some of these fields are not important for your data, others are critical. Exposure time (EXPTIME) is critical. IMTYPE helps IRAF distinguish between bias, flat, and actual data images (which are called "OBJECT") The filter (INSFILTE and/or FILTERS) is critical. For all-sky photometry, AIRMASS is critical. Various sections ending in 'SEC' tell IRAF what areas of the image to use for what processing step, are critical.

These should be correct if your image acquisition software is doing it's job. If not, or if you want to modify the header, you can do so with the 'ccdhedit' command. For example, if the real airmass for the above image was 1.53, you could change the header with 'ccdhedit m67r.fit airmass=1.53'
You can do multiple changes with commas 'ccdhedit m67r.fit airmass=1.53, exptime=62, insfilter=V'
You can also add comments to the header, such as: 'ccdhedit m67r.ft comment=peace is in the mind of the believer'. Then do 'imheader imagename l+' to see that your changes took place.

So, now that we are 'headed' (sorry!) in the right direction, let's do some image processing.

D. Getting to Know 'ccdproc'

Let's start with looking at the par file for ccdproc, type 'lpar ccdproc' and you'll get:

```
cl> lpar ccdproc
ERROR: task `ccdproc' not found
   lparam (ccdproc)
```

Gotcha! Make sure you are in the noao.imred.ccdred package. So, get back in to the ccdred package, and type 'lpar ccdproc'.

```
 cc>  .lpar ccdproc
      images = "*.fit"        List of CCD images to correct
     (output = "out*.fit")    List of output CCD images
    (ccdtype = "object")      CCD image type to correct
   (max_cache = 0)            Maximum image caching memory (in Mbytes)
      (noproc = no)           List processing steps only?\n
      (fixpix = no)           Fix bad CCD lines and columns?
    (overscan = no)           Apply overscan strip correction?
       (trim = no)            Trim the image?
     (zerocor = no)           Apply zero level correction?
     (darkcor = no)           Apply dark count correction?
     (flatcor = yes)          Apply flat field correction?
    (illumcor = no)           Apply illumination correction?
   (fringecor = no)           Apply fringe correction?
     (readcor = no)           Convert zero level image to readout correction?      (scancor = no)      Convert flat field image to scan
correction?\n
    (readaxis = "line")       Read out axis (column|line)
     (fixfile = "pambadpix.pix") File describing the bad lines and columns
     (biassec = "image")      Overscan strip image section
     (trimsec = "image")      Trim data section
```

```
      (zero = "zero.fit")     Zero level calibration image
      (dark = "")             Dark count calibration image
      (flat = "flat*.fit")    Flat field images
     (illum = "")             Illumination correction images
    (fringe = "")             Fringe correction images
 (minreplace = 1.)            Minimum flat field value
  (scantype = "shortscan")    Scan type (shortscan|longscan)
    (nscan = 1)               Number of short scan lines\n
(interactive = no)            Fit overscan interactively?
  (function = "chebyshev")    Fitting function
    (order = 1)               Number of polynomial terms or spline pieces
   (sample = "*")             Sample points to fit
  (naverage = 1)              Number of sample points to combine
  (niterate = 1)              Number of rejection iterations
 (low_reject = 3.)            Low sigma rejection factor
(high_reject = 3.)            High sigma rejection factor
      (grow = 0.)             Rejection growing radius
      (mode = "ql")
```

This is a working par file, not the default. But, let's look at the important fields. 'images' is a set of images you want to work on at once. 'output' is what the images could be called if you just didn't overwrite them. 'ccdtype' is the generic type of image to you want to work on (could be 'zero', 'flat', or 'object'). Think of it as a subset of the 'image' parameter. 'fixpix' applies a bad pixel mask to the image, more later on that step. 'overscan' uses the average pixel value in the BIASSEC area to subtract pedestal from each row. 'trim' removes the bias strip and any other parts you specified in your TRIMSEC. When 'BIASEC='image' IRAF will use the section defined in the image header. Or you could put it here. The various '...COR' parameters are correction steps. We will perform zero (bias), and flat corrections in sequence. Down farther, 'interactive' allows you to hand-tweak the bias, which is probably better left to IRAF for the beginner. Below that are the names of various images, some not yet made, that we will use in the image calibration. The rest can be left in their defaults for now. The great power of ccdproc is that you can do all the image calibration steps in one command. This is a great time saver. However, using ccdproc, we will do multiple passes through out image set, so as to understand each step. We will do this by toggling on and off the various parameters.

So, put all your images in one directory (we'll call it 'image'). This should be a working directory, so that the raw images are also stored somewhere else. You may be overwriting them, so you want a back-up set in case you (or IRAF) do something weird to them. *There is serenity in knowing you can always start from scratch.* Change to that working directory at the IRAF command line with: ' cd image'. Check that you are in the right directory with the 'path' command 'path', which should return something like: "yourcomputername!/home/username/image". Note: to go back, you either need to type the entire directory path, or do 'cd ..' which will move you back one level.

You can also do 'dir' to see what is in the directory:

```
104.3.cfg~     104i1.fts     104stobs2~     107r1.fts     m67.coo.4
104.3.config~  104i2.fts     107.coo        107r2.fts     m67.mag.1
104.5,cfg      104imset      107.mag        107r3.fts     m67.mag.2
104.ans        104imsets     107.mag.2      2try          m67.mag.3
104.cfg~       104r1.fts     107b1.fts      SA104BRI      m67b.fts
```

E. Fixing Bad Pixels

In many professional CCDs, there are bad pixels or even entire columns that don't work properly. These are there because the process of making semiconductors is not perfect, and the larger the area

of the chip, the greater the odds of something going wrong. The good news is that these defects are built into the chip, so they don't change from image to image. If they don't change, they can be corrected. The defects are most obvious on the bias images. Since a bias image is zero seconds, all you really see are the defects and the underling bias current. The way IRAF corrects these defects is to interpolate between the bad pixel (or series of pixels such as in a column) and adjacent pixels that are not damaged. It then replaces the "bad" pixel values with the interpolated ones.

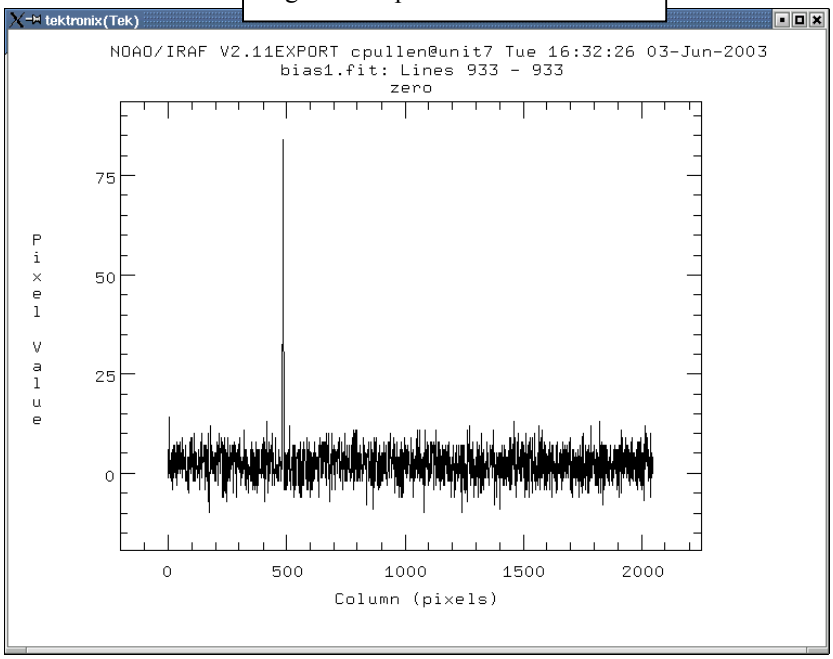
You might well ask yourself: “Is this legitimate? Wouldn't it be better to just not use data contaminated by a physical defect in the chip?” Probably! Except it is very hard to control exactly what pixels are going to be needed down the road. So, let’s just fix them and move on.

Since the bad pixels are physically on the chip, you need to make a bad pixel mask that tells IRAF which pixels are bad and need interpolation. An example of a mask made for the camera that took my images is in the Appendix. Each line is a coordinate set for the untrimmed image. "5 334 1 4" means "from pixel column 5 to column 334, and row 1 to row 4, inclusive”.

So, one must specify which pixels and/or columns you want to fix. The example mask was made "with much cursing" (Gay, 2003) over time. The key point to making a mask is to identify the pixels properly. Note that they are integers. If whatever you are doing is giving you fractional row:column pixel coordinates, you are doing something wrong (however, star centroids may well be determined to fractional pixel values).

One way to determine the grossest errors, like a bad column, is to use 'imexamine', place your cursor over the bad pixel (use the magnifier) and hit 'x'. This outputs: 1107.00 1213.00 5.08008 showing the column and row coordinates, and the value of the pixel, respectively. You can also do ‘l’ for a line plot (Figure 4). Note that I am zoomed in on the image (see the blue box on the magnifier. So, I zoom out, I can see that the bad column is the entire height of the image, from row 1 to row 2048. But, while zoomed out, if I try 'x', I get different coordinates for the column number!: 1105.00 1988.00 7.08008

Figure 4 – Spike is the bad column



To show the whole image, your viewer is binning (using blocks of the image). Try moving your cursor with your left and right arrow buttons. Note the coordinates on the viewer - they are changing in blocks of 4 or more pixels! So, to get accurate coordinates, you have to be zoomed in on the image so that you are moving in one-pixel steps. The better way to hunt for defects when zoomed is to drag the magnifying blue box about the image with your mouse. That way, you can see the whole image in sections, but not loose pixel

coordinate resolution.

The point of this exercise is that making up bad pixels masks by inspection is a pain. There are other ways. One is to take a flat field image of two different exposure lengths, then subtract them (Massy, 1997; Wells & Bell, 1994). The resultant "image" is your bad pixel mask, because it only shows the "high points". This process is covered in detail in the references. The good news is you only have to get the mask right, once, then use it over and over. So, given that the "bad pixel mask fairy" provides you with a mask, as she did for me, let's fix those pesky bad pixels.

Going back to epar ccdproc, let's modify the parameter file to fix the bad pixels with fixpix:

```
cc> lpar ccdproc
      images = "*.fit"        List of CCD images to correct
    (output = "out*.fit")     List of output CCD images
    (ccdtype = "")           CCD image type to correct
  (max_cache = 0)             Maximum image caching memory (in Mbytes)
     (noproc = no)           List processing steps only?\n
     (fixpix = yes)          Fix bad CCD lines and columns?
   (overscan = no)           Apply overscan strip correction?
      (trim = no)           Trim the image?
    (zerocor = no)           Apply zero level correction?
    (darkcor = no)           Apply dark count correction?
    (flatcor = yes)         Apply flat field correction?
   (illumcor = no)           Apply illumination correction?
  (fringecor = no)           Apply fringe correction?
    (readcor = no)           Convert zero level image to readout correction?
    (scancor = no)           Convert flat field image to scan correction?\n
  (readaxis = "line")         Read out axis (column|line)
    (fixfile = "pambadpix.pix") File describing the bad lines and columns
    (biassec = "image")       Overscan strip image section
    (trimsec = "image")       Trim data section
       (zero = "zero.fit")    Zero level calibration image
       (dark = "")           Dark count calibration image
       (flat = "flat*.fit")   Flat field images
```

It will confirm the image set (no parenthesis) and then run it by itself. Note that we are apply this to all images, so change 'ccdtype' to all with "" (double quotes). Run ccdproc again, then display a bias image and see what it now looks like. In my case, Fig. 4a went to 4b. Magic!

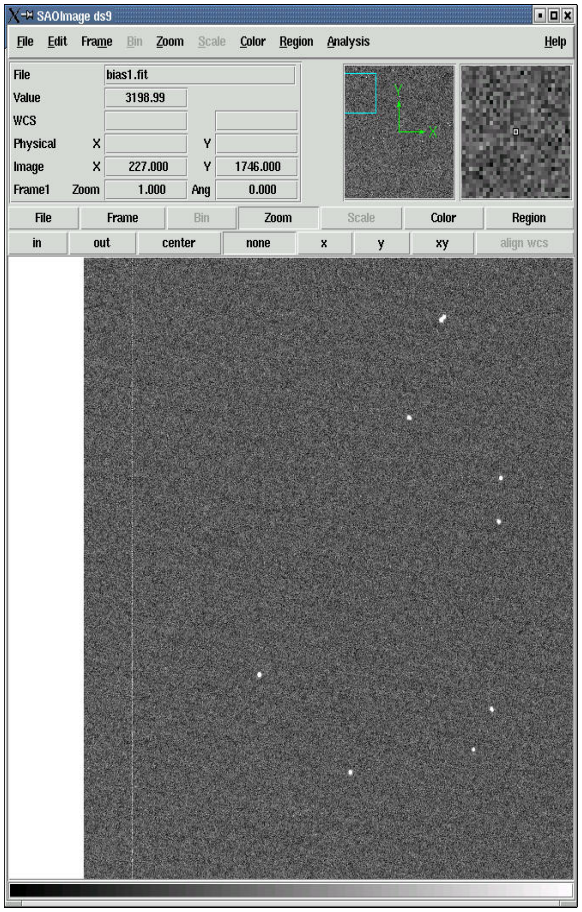


Figure 4a - defects

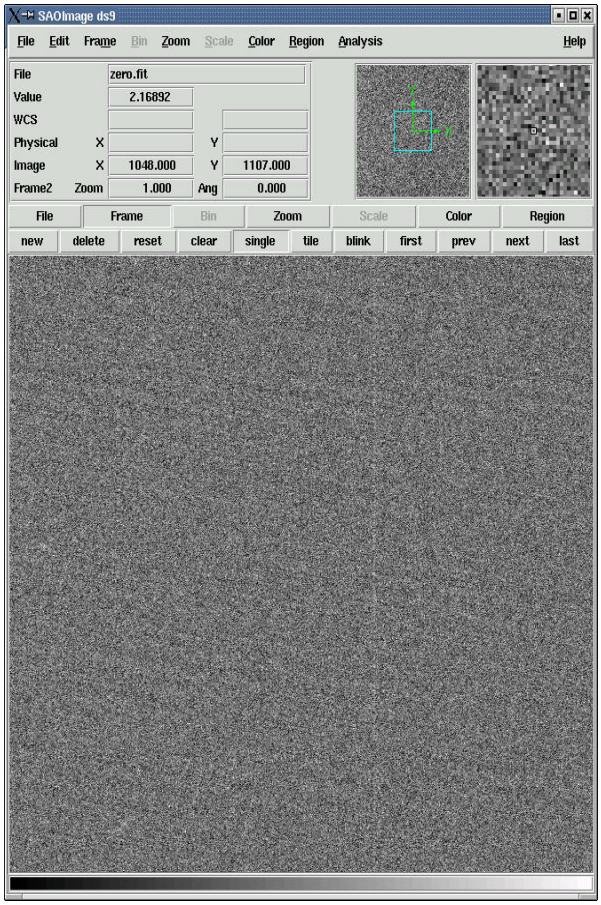


Figure 4b – Mostly Fixed

F. Overscan Corrections

So, now let's do the first part of the overscan correction. Toggle overscan to 'on' with an 'epar ccdproc' and turn everything else off so that your ccdproc file looks something like:

```
 images = "*.fit"         List of CCD images to correct
    (output = "out*.fit")    List of output CCD images
   (ccdtype = "")            CCD image type to correct
  (max_cache = 0)            Maximum image caching memory (in Mbytes)
    (noproc = no)            List processing steps only?\n
    (fixpix = no)            Fix bad CCD lines and columns?
  (overscan = yes)           Apply overscan strip correction?
     (trim = no)             Trim the image?
   (zerocor = no)            Apply zero level correction?
   (darkcor = no)            Apply dark count correction?
   (flatcor = no)            Apply flat field correction?
  (illumcor = no)            Apply illumination correction?
  (fringecor = no)           Apply fringe correction?
```

Once your par file is right, run 'ccdproc'

G. Overscan Trimming

Now that we've used the bias strip to adjust for row-by-row bias, we can get rid of it on all our images. Why? It just takes up memory, and looks ugly on our images. So, go back to epar ccdproc and toggle off 'overscan' and toggle on 'trim' as follows:

```
images = "*.fit"        List of CCD images to correct
    (output = "out*.fit")    List of output CCD images
   (ccdtype = "")            CCD image type to correct
  (max_cache = 0)             Maximum image caching memory (in Mbytes)
    (noproc = no)           List processing steps only?\n
    (fixpix = no)           Fix bad CCD lines and columns?
  (overscan = no)           Apply overscan strip correction?
     (trim = yes)           Trim the image?
   (zerocor = no)           Apply zero level correction?
   (darkcor = no)           Apply dark count correction?
   (flatcor = no)           Apply flat field correction?
```

Run ccdproc again.

Now, look at an image with 'display' and zoom on the right side. There should be no bias strip . It will also have trimmed off the edges of the frame specified in the TRIMSEC part of the image header, or imputed into the same part of the 'ccdproc' par file,

H. Dark Subtraction

Thinned, back-illuminated CCDs have little dark current, so I did not do a dark subtraction. However, most amateur CCDs do have dark current, and it must be dealt with. Basically, the procedure is similar to what you'll see below for making master flats and bias images, using the 'ccdred' task 'darkcombine'. If you make a master dark per Berry and Burnell (2000) (25+ images at an exposure time at least 5 times your longest exposure) IRAF can use a single median combined image, the “master dark”, and apply it to all your frames. It will adjust the value of the dark subtraction based on the ratio of the exposure times. This is called a "scaled dark". Note, that you must subtract a master bias image from each of your darks prior to combination.

There are potential problems with scaled darks. You are trusting that your dark current is truly linear, that there are no light-leaks in the system, and that the temperature is really constant. So, many people want to make a master dark of at least 10 to 25 images for each exposure time and camera temperature you used in a given run. You then make master darks using 'darkcombine' for each exposure time (and temperature if need be).Then using 'ccdproc' subtract, the appropriate dark from the object and flat images. Since the bias is contained in the dark, you do not do bias image subtraction from your image set.

I. Making a Master Bias Frame and Applying Bias

Our next step is to correct for additional bias by subtracting a master bias image. But first you have to make it! We will use 'zerocombine' for that task.

Epar zerocombine and you should get:

```
input = "bias*.fit"     List of zero level images to combine
  (output = "zero.fit")     Output zero level name
 (combine = "median")       Type of combine operation
  (reject = "minmax")       Type of rejection
 (ccdtype = "zero")         CCD image type to combine
 (process = no)             Process images before combining?
  (delete = no)             Delete input images after combining?
 (clobber = no)             Clobber existing output image?
  (scale = "none")          Image scaling
 (statsec = "")             Image section for computing statistics
   (nlow = 0)               minmax: Number of low pixels to reject
  (nhigh = 1)               minmax: Number of high pixels to reject
  (nkeep = 1)               Minimum to keep (pos) or maximum to reject (neg
  (mclip = yes)             Use median in sigma clipping algorithms?
 (lsigma = 3.)              Lower sigma clipping factor
 (hsigma = 3.)              Upper sigma clipping factor
(rdnoise = "rdnoise")       ccdclip: CCD readout noise (electrons)
   (gain = "gain")          ccdclip: CCD gain (electrons/DN)
 (snoise = "0.")            ccdclip: Sensitivity noise (fraction)
  (pclip = -0.5)            pclip: Percentile clipping parameter
  (blank = 0.)              Value if there are no pixels
   (mode = "ql")
```

'input' is the images you want to use to combine. Remember our file naming conventions? Here is where you use them. 'output' is what the combined bias frame will be called. 'combine' is the statistical method you want to use. I prefer median combine for bias and flats, but you could use 'mode' as well. 'reject' for a bias frame is suggested to be 'minmax'. 'ccdtype' is another way to specify which images you would use from your 'input' set. So, with 'image=*.fit' you could use 'ccdtype=zero' and still only combine the bias images. 'process' is for combining steps into one grand ccdproc run. 'delete' is to get rid of your original bias images to keep them from cluttering up your directory -- use it at your own risk!

So, now that we are all set up, lets try 'zerocombine'. It will produce the image zero.fit (Fig.2b). Display zero.fit on your viewer, as well as one of the bias frames used to make it. Go to imexamine (which works in the ccdred task, no need to move back to the cl> level) and look at the same pixel coordinates with 'm' (image statistics).

For the master bias (zero.fit):

```
#          SECTION    NPIX     MEAN   MEDIAN   STDDEV      MIN      MAX
[1104:1108,1065:1069]      25    98.56     96.    26.88     48.     168.
 [850:854,1143:1147]       25    100.2     104.   28.39     40.     152.
```

For one of the original bias images:

```
 [1240:1244,909:913]       25     1.64     1.08    2.931    -3.92     7.08
  [932:936,846:850]        25     2.12     1.08    4.036    -5.92     9.08
```

By median combining many bias frames, you have lowered the overall noise, which was the goal of the exercise. How many frames is enough? Some say as many as 25 to 50! The example was done with 5. Note the apparent residual column defect on Fig. 2b. It is really an artifact of the viewer contrast, as it is invisible on a line plot.

Now, let's apply that master bias (zero.fit) to the rest of our frames with ccdproc:

```
    images = "*.fit"         List of CCD images to correct
    (output = "out*.fit")    List of output CCD images
   (ccdtype = "object", "flat")      CCD image type to correct
  (max_cache = 0)            Maximum image caching memory (in Mbytes)
    (noproc = no)            List processing steps only?\n
    (fixpix = no)            Fix bad CCD lines and columns?
   (overscan = no)           Apply overscan strip correction?
      (trim = no)            Trim the image?
   (zerocor =yes))           Apply zero level correction?
   (darkcor = no)            Apply dark count correction?
   (flatcor = yes)           Apply flat field correction?
  (illumcor = no)            Apply illumination correction?
 (fringecor = no)            Apply fringe correction?
   (readcor = no)            Convert zero level image to readout correction?
   (scancor = no)            Convert flat field image to scan correction?\n
  (readaxis = "line")        Read out axis (column|line)
   (fixfile = "pambadpix.pix") File describing the bad lines and columns
   (biassec = "image")       Overscan strip image section
   (trimsec = "image")       Trim data section
     (zero = "zero.fit")     Zero level calibration image
     (dark = "")             Dark count calibration image
     (flat = "flat*.fit")    Flat field images
```

Note that for 'ccdtype' this ccdproc run will subtract the bias from both the flat field and object images. Run ccdproc, and move on to flat fielding!

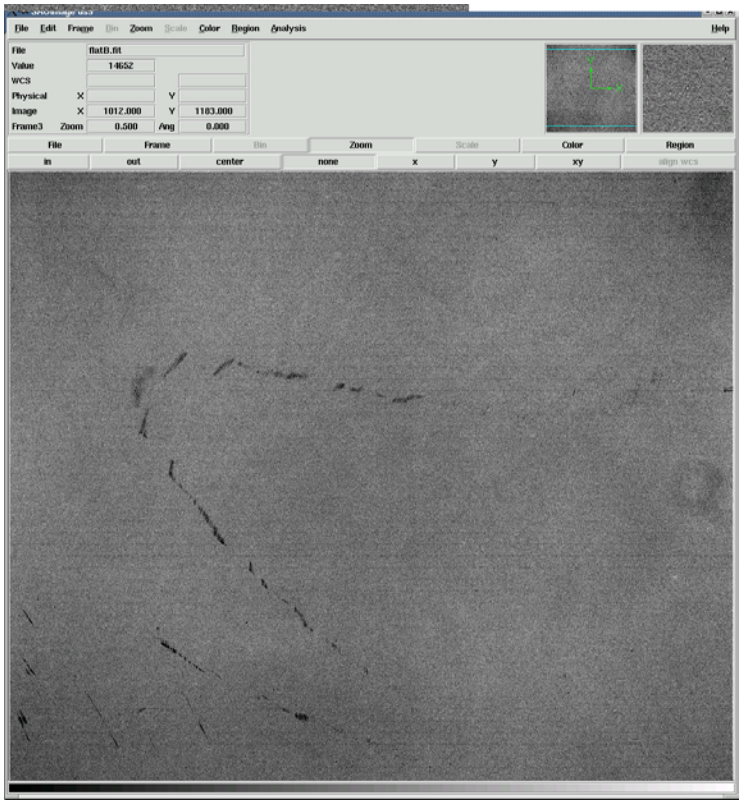
J. Making Master Flat Field Frames and Applying Flat Field Corrections

Just like we made our master bias frame, we must make master flat frames for each filter used. You probably have guessed how we are going to do that – 'flatcombine'!

Look at the param file for 'flatcombine':

```
cc> lpar flatcombine
       input = "flat*.fit"     List of flat field images to combine
    (output = "flat")          Output flat field root name
   (combine = "median")        Type of combine operation
    (reject = "crreject")      Type of rejection
   (ccdtype = "flat")          CCD image type to combine
   (process = no)              Process images before combining?
   (subsets = yes)             Combine images by subset
parameter?
    (delete = no)              Delete input images after
combining?
   (clobber = no)              Clobber existing output image?
     (scale = "mode")          Image scaling
   (statsec = "")              Image section for computing
statistics
      (nlow = 1)               minmax: Number of low pixels to
reject
     (nhigh = 1)               minmax: Number of high pixels to
reject
     (nkeep = 1)               Minimum to keep (pos) or maximum
to reject (neg
     (mclip = yes)             Use median in sigma clipping
algorithms?
     (lsigma = 3.)             Lower sigma clipping factor
     (hsigma = 3.)             Upper sigma clipping factor
   (rdnoise = "0.")            ccdclip: CCD readout noise
(electrons)
```

Figure 5 – R Master Flat



```
    (gain = "1.")         ccdclip: CCD gain (electrons/DN)
  (snoise = "0.")         ccdclip: Sensitivity noise (fraction)
   (pclip = -0.5)         pclip: Percentile clipping parameter
   (blank = 1.)           Value if there are no pixels
    (mode = "ql")
```

Are things beginning to look familiar? They should!

Input is as before, as is output. For output, "root name" means it will name the file flatX.fit where X is the filter name (BVRI; O,1,2,3,4 - whatever is in the header by the keyword FILTERS). 'combine' is again set to median. 'reject' is set for cosmic rays - 'ccreject'. 'subsets' will keep your R flats from getting mixed up with your B flats. Leave the rest alone at this point.

Now, run ccdproc and you will get a median combine master flat for each filter. Take a look at them in display. Use 'imexamine' to look for hot pixels, or other problems.

Note that one additional step often needed is to take the median of the image and divide each pixel by that value. This creates a "normalized" flat, with individual pixel values hovering around 1. You can do this step, if you wish, with the 'imarith' command. However, 'ccdproc' will do this for you when applying the flat to the object image.

Let's do that now -once more to ccdproc:

```
cc> lpar ccdproc
      images = "*.fit"        List of CCD images to correct
    (output = "out*.fit")     List of output CCD images
   (ccdtype = "object")       CCD image type to correct
  (max_cache = 0)             Maximum image caching memory (in Mbytes)
    (noproc = no)             List processing steps only?\n
    (fixpix = no)             Fix bad CCD lines and columns?
  (overscan = no)             Apply overscan strip correction?
      (trim = no)             Trim the image?
   (zerocor = no)             Apply zero level correction?
   (darkcor = no)             Apply dark count correction?
   (flatcor = yes)            Apply flat field correction?
  (illumcor = no)             Apply illumination correction?
 (fringecor = no)             Apply fringe correction?
   (readcor = no)             Convert zero level image to readout correction?
   (scancor = no)             Convert flat field image to scan correction?\n
  (readaxis = "line")         Read out axis (column|line)
   (fixfile = "pambadpix.pix") File describing the bad lines and columns
   (biassec = "image")        Overscan strip image section
   (trimsec = "image")        Trim data section
      (zero = "zero.fit")     Zero level calibration image
      (dark = "")             Dark count calibration image
      (flat = "flat*.fit")    Flat field images
```

Go ahead and run it, then look at the headers of your object fields. Here is an example of the final lines in a FITS header from a calibrated image:

```
FIXPIX  = 'May 10 15:02 Bad pixel file is pambadpix.pix'
CCDPROC = 'May 10 15:17 CCD processing done'
TRIM    = 'May 10 15:09 Trim data section is [2:2047,2:2047]'
OVERSCAN= 'May 10 15:09 Overscan section is [2057:2072,2:2047] with mean=3204.4'
ZEROCOR = 'May 10 15:09 Zero level correction image is zero.fit'
LTV1    =     2048.00006509877
```

```
LTV2   =    2047.99993490121
FLATCOR = 'May 10 15:17 Flat field image is flatR.fit with scale=25884.08'
```

IRAF documents all your changes to the image in the header.

The short version is also helpful:

```
cc> imheader m67r
m67r[2046,2046][real]: M67 R
```

It tells us that the image has been trimmed to 2046 by 2046 pixels. It is now "real", which means 32 - bit floating point.

K. Registering Images or Performing Astrometry

We are, unfortunately, not out of the woods yet. For our photometry, we will need to identify specific stars in a way IRAF can understand. This means pixel coordinates or a WCS astrometric solution. An astrometric solution provides header information to allow IRAF and DS9 to display coordinates in RA and DEC to some precession epoch. These are much preferred over just pixel X and Y, because you can then identify stars by their "proper names", RA and DEC.

As it stands right now, IRAF doesn't really have an astrometry routine. SAO puts out a WCS calculation tool called (oddly enough) WCS-Tools for use in LINUX. WCS-Tools is also free. Unfortunately for me, it would be another project to get it working! A friend who is a geophysicist and lives and breathes both Linux and astronmetry could not get WCS tools to work (Billings, 2003). I attempted to use the LINUX planetarium software Xephem that has a WCS tool. However, it would not work on any of the object images, presumably due to their size, although "human error" (me!) cannot be ruled out either. So, pixel coordinates were used to identify specific stars. This creates another problem.

In any of the object images, a given star is not at the same coordinates. So, the images had to be "registered" such that a given star was at the same place in all the images of that field. If you think of a FITS image as a 3D plot of z, y, and z (where x = row, y= column, z= the value of the pixel) it is easy to visualize how images are registered. One takes an image of a given field, calls that the master, and coordinates are compiled for a number of clear, well defined stars in each image. One can then calculate the amount of x,y transformation that is needed, and add or subtract these values from the entire matrix of x,y,z coordinates. If we were using photographic negatives, you could imagine moving the film around until all the stars line up.

While the concept is simple, the IRAF execution was not. At the time I was trying to register the images, I was having great inner turmoil with IRAF, and the tasked looked very daunting. So, I took the easy, yet sinful, way past this karmic bump, and used the Windows software Mira 6.2 to do the registration. In MIRA one loads the images into the program, clicks on the stars one wants to use as registration points, and tells it to register the image stack to those stars. It worked fine, although it took over 20 minutes to process an image stack of 9 SA107 images due to their 16 MB (each) size! This section will be rewritten for IRAF after I have had a chance to figure it out.

There is Windows camera software that will perform precision astrometry on images as they are taken. It's called PinPoint, which is part of the ASCOM Initiative (http://www.dc3.com). Use of this

software will make astrometry at the precision needed for my work just part of taking the image - I hope!

Save your calibrated images in a different directory, and let's try to extract some information from them!

IV. INSTRUMENTAL PHOTOMETRY

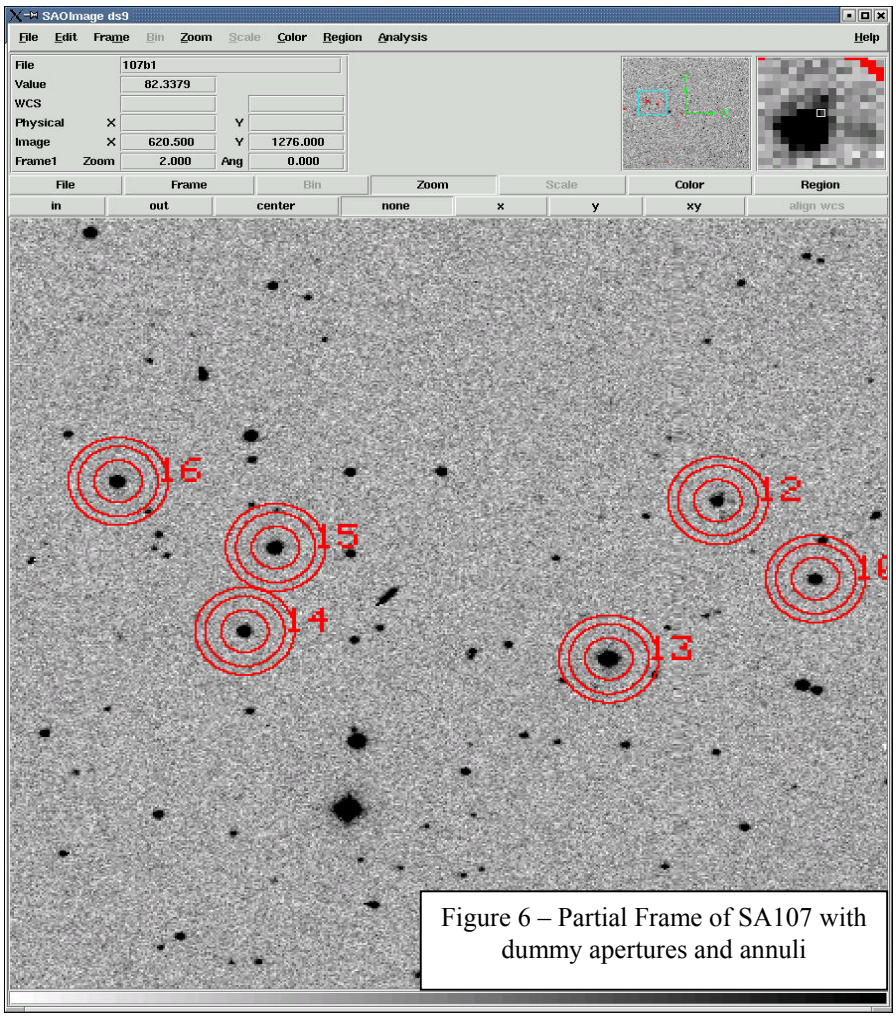


Figure 6 – Partial Frame of SA107 with dummy apertures and annuli

Don't tell me how difficult the Way. The bird's path, winding far, is right before you. Water of the Dokei Gorge, you return to the ocean, I to the mountain.

Hofuku Seikatsu

A. Identifying Standard Stars

Figure 6 shows part of SA107. It, and many others, has been calibrated by Arlo Landolt (Landolt 1992) to act as UBVRI standards. That means that their magnitude and color is established and referenced to the original equatorial UBV stars of Landolt and Morgan. However, finding out which star is which can be difficult. Nevertheless, correct identification is critical.

Unlike most amateur photometric software, one cannot directly identify stars with a point-and-click interface. But you can do almost the same thing by making up a coordinate (.coo) file for each field of your stars of interest.

First, we have to decide which Landolt stars we want to use. If you said "all of them" you are both right and wrong. The more standards you use, over the widest range of color, the better transformation and extinction coefficients you will get. However, not all Landolt stars are created equal. Many of the "standard" stars were observed on just one or two nights, for only a few observations. Others may have dozens of observations, over many nights. Given this fact, you will not be surprised to learn that several variable stars are among Landolt's standards! So, it balance number vs quality when choosing standards. For the purpose of my project, I choose the standard stars used by Dr. Gay in her research.

Another issue is simply finding which star is which. The original plates from Landolt 1992 are fairly large scale, and even in an offset press published reprint (which was sent to me by Dr. Landolt upon request), it can be difficult to see which star is which in some cases. Some photometrists have made their own finder charts based on their own CCD images, if you can get some of these from a trusted source they are worth their weight in gold. But, given that you have to use open resources, you can access the Landolt 1992 catalog and finder plates on-line from ESO LaSilla. Close-up images of some of the Landolt stars, organized by RA, can be found at Lick Observatory (URLs in Resources)

Now that you've decided which stars to use, you need to tell IRAF their coordinates. Open an image in 'display', and execute 'imexamine'. Find each star on your image, and record it's pixel coordinates with ','. That is one of the quick photometry routines that will give you output like:

```
#   COL    LINE    RMAG     FLUX      SKY   N  RMOM ELLIP    PA     PEAK MFWHM
 940.97  1132.59   13.28  48806.5   111.12  78  2.34  0.111  -9.8  7300.69  2.33
1050.24 1066.43   15.00   9988.9   110.39  80  2.31 0.152  -6.6  1520.14  2.29
1126.96 1072.26   14.45  16623.1   111.43  77  2.23 0.174 -16.2  2709.07  2.13
 842.48  874.10   16.16   3441.8   111.37  80  2.31 0.136  15.6   547.11  2.11
```

Note that the pixel coordinates are the centroids of the stars, so you don't have to be too careful where you put your cursor. Note also the (MFWHM), this figure is in pixels, and will be used later to set aperture size. Finally, note that fractional coordinates are OK for this application.

Once you get this data, cut and paste it into a text file, say 107.coo (highlight the output in your Xwindow, open a text editor, place the cursor in it, and click both mouse buttons at once). All we need are the coordinates, so you can delete all other information by hand.

Now, you might want to check that you have everything correct. One way to do this is to mark the stars with the coordinates found in the .coo file (Figure 6, above). That is done with 'tvmark', in the digiphot.daophot package. Epar 'tvmark'

```
da> lpar tvmark
       frame = 1              Default frame number for display
      coords = "107.pam.coo"   Input coordinate list
    (logfile = "")           Output log file
    (autolog = no)            Automatically log each marking command
   (outimage = "")            Output snapped image
  (deletions = "")           Output coordinate deletions list
   (commands = "")             Image cursor: [x y wcs] key [cmd]
       (mark = "circle")      The mark type
      (radii = "12,20,25")     Radii in image pixels of concentric circles
    (lengths = "0")           Lengths and width in image pixels of concentric
       (font = "raster")      Default font
      (color = 204)           Gray level of marks to be drawn
      (label = no)            Label the marked coordinates
     (number = yes)             Number the marked coordinates
   (nxoffset = 20)            X offset in display pixels of number
   (nyoffset = 0)             Y offset in display pixels of number
  (pointsize = 5)             Size of mark type point in display pixels
     (txsize = 2)             Size of text and numbers in font units
  (tolerance = 1.5)             Tolerance for deleting coordinates in image pix
(interactive = no)              Mode of use
       (mode = "ql")
```

The 'frame' is the DS9 frame the image is in. 'coods' is the .coo file you made. A 'outimage' would have the marks embedded in it. 'mark type' is a circle, box, point, or none (which can be useful for

just numbering stars. 'radi' is in pixels, and you can simulate an aperture and background annulus , as I did above. 'color' is a code for the color of the mark, the help file has all the options. 'number' numbers the markings in order of their appearance in the .coo file The 'offset' is how much off the center of the coordinate to mark the number.

'tvmark' can be invoked with:

```
da> display 107r1 1
da> tvmark
Default frame number for display (2): 1
Input coordinate list (107.pam.coo):
```

If you want to extract this image for later use, such as in a paper, you can either do a screen capture, or make it a 'snap' image from the 'tvmark' par file.

B. Using ‘daofind' for Star Identification

For your program stars, you may be interested in just a few, or as many as possible in the field. In my CMD project, I wanted all of them in M67. IRAF has a task (unique among photometric software) for automatically finding large numbers of stars in a field, called 'daofind', also in the daophot package with tvmark.

Figure 7 is my M67 field. Let’s look at the par file for daofind:

```
da> lpar daofind
       image = "m67r"          Input image(s)
      output = "m67.coo.4"     Output coordinate file(s) (default: image.coo.?
   (starmap = "")              Output density enhancement image(s)
    (skymap = "")              Output sky image(s)
  (datapars = "")              Data dependent parameters
  (findpars = "")              Object detection parameters
  (boundary = "nearest")       Boundary extension (constant|nearest|reflect|wr
  (constant = 0.)              Constant for boundary extension
(interactive = no)             Interactive mode ?
    (verify = )_.verify)       Verify critical daofind parameters ?
    (update = )_.update)       Update critical daofind parameters ?
   (verbose = )_.verbose)      Print daofind messages ?
  (graphics = )_.graphics)     Graphics device
   (display = )_.display)      Display device
 (icommands = "")              Image cursor: [x y wcs] key [cmd]
 (gcommands = "")              Graphics cursor: [x y wcs] key [cmd]
      (mode = "ql"
```

'image' is the image. 'output' is the output file name, a .coo extension will tell you it it is a coordinate file. But now things get complicated. 'datapars' and 'fitpars' have their own par file!

Edit it by putting your cursor on that line in epar, and type ':e'. For datapars, we get:

```
PACKAGE = daophot
  TASK = datapars

(scale  =                1.) Image scale in units per
pixel
(fwhmpsf=                2.5) FWHM of the PSF
in scale units
(emissio=               yes) Features are positive
?(sigma  =               0.) Standard deviation of
background in counts
(datamin=            INDEF) Minimum good
data value
(datamax=            INDEF) Maximum good
data value
(noise  =            poisson) Noise model
(ccdread=                ) CCD readout noise
image header keyword
(gain   =                ) CCD gain image header
keyword
(readnoi=                0.) CCD readout noise in
electrons
(epadu  =                1.) Gain in electrons per
count
(exposur=            EXPTIME) Exposure time
image header keyword
(airmass=            AIRMASS) Airmass image
header keyword
(filter =            FILTERS) Filter image header
keyword
(obstime=                UT) Time of observation
image header keyword
(itime  =               30.) Exposure time
(xairmas=     1.7070000171661) Airmass
(ifilter=                R) Filter
(otime  =         6:06:48.53) Time of
observation
(mode   =                ql)
```

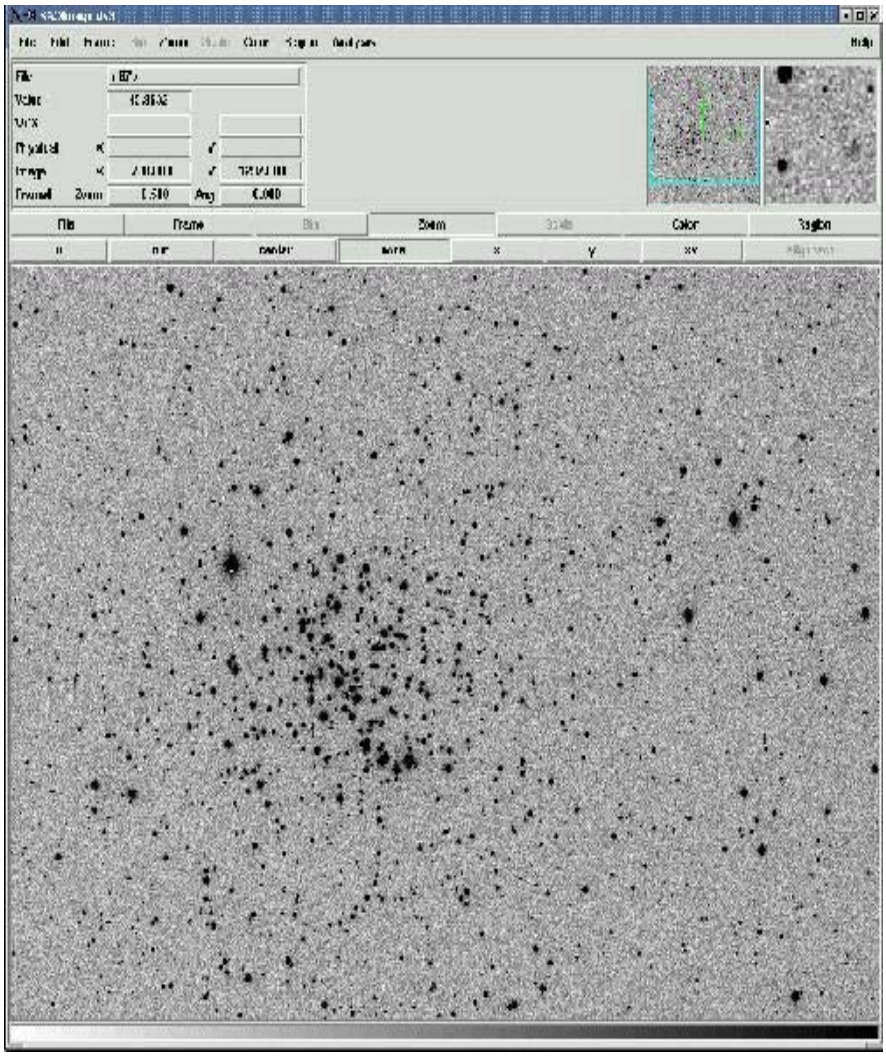


Figure 7 – Most of M67

and for fitpars we get:

```
PACKAGE = daophot
  TASK = findpars

(thresho=                4.) Threshold in sigma for feature detection
(nsigma =                1.5) Width of convolution kernel in sigma
(ratio  =               1.) Ratio of minor to major axis of Gaussian kernel
(theta  =               0.) Position angle of major axis of Gaussian kernel
(sharplo=               0.2) Lower bound on sharpness for feature detection
(sharphi=               1.) Upper bound on sharpness for  feature detection
(roundlo=              -1.) Lower bound on roundness for feature detection
(roundhi=               1.) Upper bound on roundness for feature detection
(mkdetec=               yes) Mark detections on the image display ?
(mode   =               ql)
```

'datapars' and 'fitpars' tell daofind what defines a "star" of interest to you. You can screen out stars based on minimum or maximum pixel value (noise or saturated), FWHM, or specific key words in an image, so it doesn't try to find stars in your flats. Using the default values, more or less, lets try to find some stars:

da> daofind
Input image(s) (m67r):
Output coordinate file(s) (default: image.coo.?) (m67.coo.example):

FWHM of features in scale units (2.5) (CR or value):
    New FWHM of features: 2.5 scale units 2.5 pixels
Standard deviation of background in counts (0.) (CR or value):
    New standard deviation of background: 0. counts
Detection threshold in sigma (4.) (CR or value):
    New detection threshold: 4. sigma 0. counts
Minimum good data value (INDEF) (CR or value):
    New minimum good data value: INDEF counts
Maximum good data value (INDEF) (CR or value):
    New maximum good data value: INDEF counts

(many, many, many pages of screen output later...)

1632.18 2044.22   INDEF   0.373 -0.297 -0.302
93069
1659.36 2044.74   INDEF   0.842 -0.281   0.572
93070
1678.52 2044.46   INDEF   0.687 -0.797 -0.674
93071
379.00 2046.02   INDEF   0.541 -0.525 -0.821
93072
1198.77 2046.00   INDEF   0.290   0.897   0.485
93073

threshold: 0. relerr: 1.140 0.2 <= sharp <= 1. -1. <= round <= 1.

IRAF ran away, producing a detection for nearly every pixel (note the final number of detections: 93,073). Let's try again, and try to rein it in a bit.

First, discard that .coo file ' del m67.coo.example'. Then:

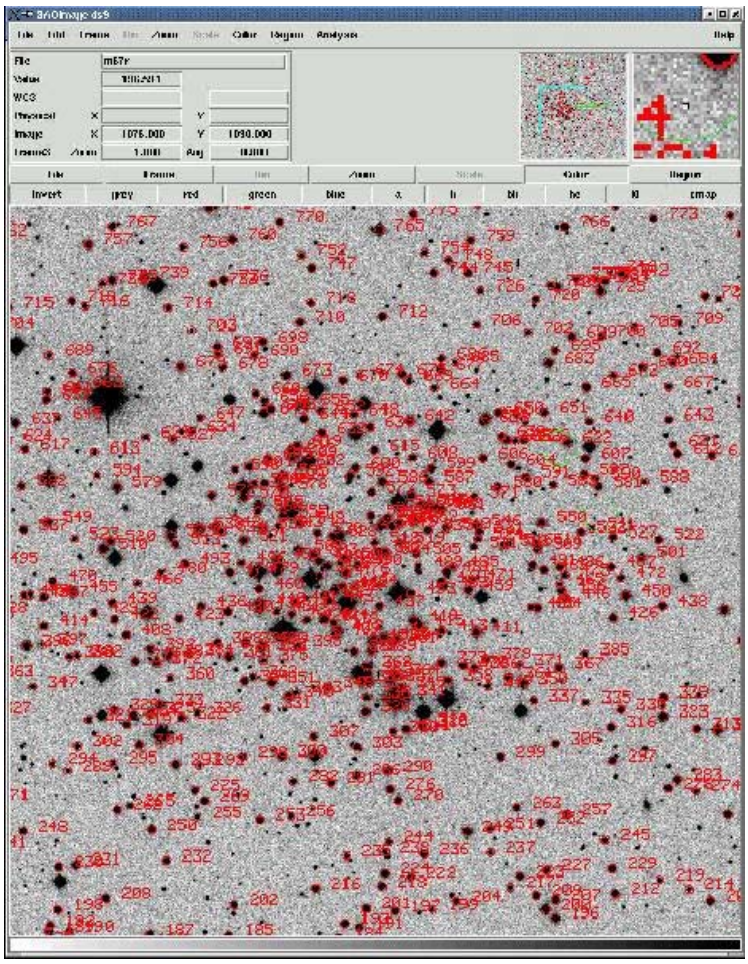


Figure 8 – daofind detection at the edge of M67

da> daofind
Input image(s) (m67r):
Output coordinate file(s) (default: image.coo.?) (m67.coo.example):
FWHM of features in scale units (2.5) (CR or value):
    New FWHM of features: 2.5 scale units 2.5 pixels
Standard deviation of background in counts (0.) (CR or value)**: 500**
    New standard deviation of background: 500. counts
Detection threshold in sigma (4.) (CR or value):
    New detection threshold: 4. sigma 2000. counts
Minimum good data value (INDEF) (CR or value): **500**
    New minimum good data value: 500. counts
Maximum good data value (INDEF) (CR or value): **50000**
    New maximum good data value: 50000. counts
…

1336.31 1985.12   -2.810   0.643 -0.220 -0.378   943
607.48 1996.66   -4.849   0.597 -0.197 -0.110   944

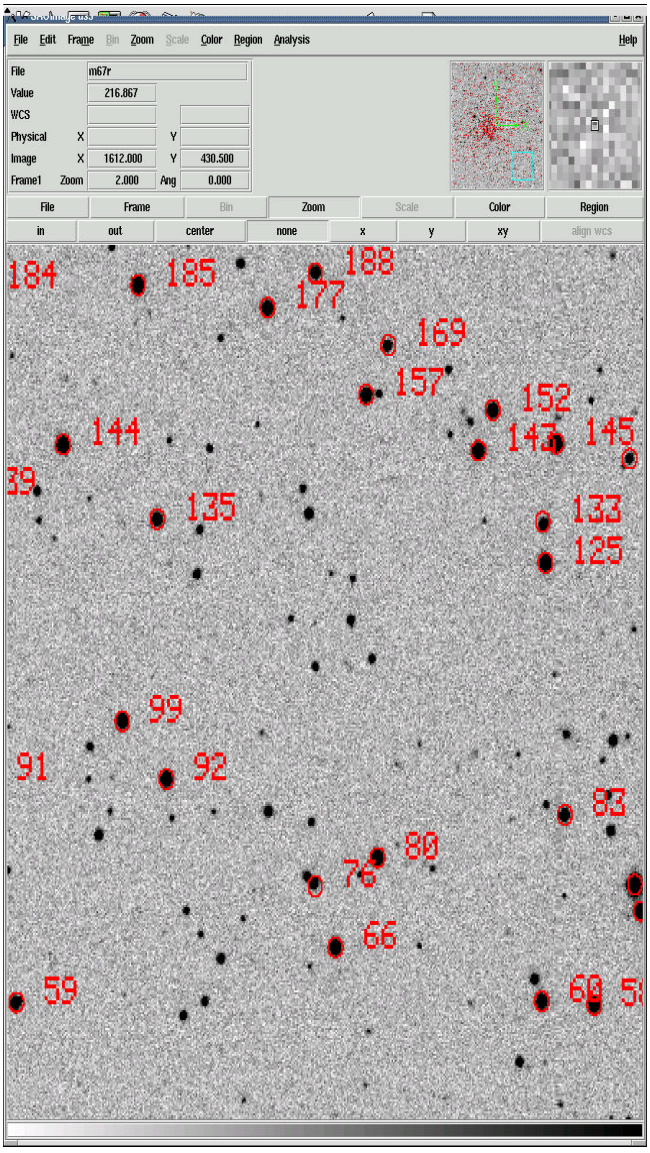
```
1053.98  2005.81   -2.561   0.615   0.347  -0.901   945
 179.96  2006.95   -2.576   0.608  -0.158   0.320   946
1869.94  2008.86   -3.355   0.653   0.007  -0.066   947
 259.35  2013.66   -4.177   0.594  -0.168   0.019   948
1198.58  2013.70   -2.346   0.609   0.036  -0.200   949
 495.01  2028.77   -1.826   0.593  -0.125   0.324   950
1192.94  2033.69   -3.202   0.647   0.011  -0.007   951
 984.83  2041.23   -2.438   0.612  -0.438  -0.112   952
```

I want to include all the stars that are adequately exposed, but not stars that are saturated. One way to tell this is to zoom in on a small section that has faint non-detected stars, Figure 9, as well as bright non- detected stars and check them out with imexamine 'a' quick photometry. Its an iterative process, so be prepared to try different values. Finally, using the following values:

```
da> daofind
Input image(s) (m67r):
Output coordinate file(s) (default: image.coo.?)
(m67.coo.example2):

FWHM of features in scale units (2.5) (CR or value):
      New FWHM of features: 2.5 scale units  2.5 pixels
Standard deviation of background in counts (0.) (CR or value):
250
      New standard deviation of background: 250. counts
Detection threshold in sigma (4.) (CR or value):
      New detection threshold: 4. sigma 1000. counts
Minimum good data value (INDEF) (CR or value):
      New minimum good data value: INDEF counts
Maximum good data value (INDEF) (CR or value): 50000
```

Figure 9 – Close up to evaluate daofind selection



I find that the selected stars have reasonable errors (for the most part) but the non-selected do not, or are saturated (peak >50,000 counts).

da> imexamine SELECTED

```
OL   LINE    RMAG    FLUX     SKY   N  RMOM ELLIP   PA
PEAK MFWHM
1131.25  422.54   14.01  24840.8   216.78  81  2.75 0.148  35.0
3210.21  2.39
#   COL    LINE    COORDINATES
#    R    MAG    FLUX    SKY    PEAK    E    PA BETA
ENCLOSED   MOFFAT DIRECT
1131.26  422.54 1131.26 422.54
  6.97  13.98  25502.   216.3   3198. 0.23   30 12.0     2.36     2.41
2.32
1116.67  371.62 1116.67 371.62
  6.90  12.23 128470.   217.9  17209. 0.04   14 5.77     2.26
2.34   2.30
1093.00  356.17 1093.00 356.17
  6.59  12.94  66718.   218.2   9016. 0.02    2 4.09     2.21     2.34
2.20
1097.19  343.35 1097.19 343.35
  6.88  14.40  17355.   219.   2321. 0.08    5 12.0     2.32     2.40
2.30
```

NOT SELECTED

```
#    R   MAG   FLUX    SKY    PEAK    E   PA BETA ENCLOSED   MOFFAT DIRECT
1113.30  417.62 1113.30 417.62
  7.01  17.68   850.5   217.3   INDEF 1.01   39 INDEF     2.36    INDEF   2.32
1167.99  402.77 1167.99 402.77
  7.43  16.87   1782.   213.6  167.3 0.15   29 6.35     2.49     2.83   2.49
1136.11  377.05 1136.11 377.05
  6.79  15.96   4118.   217.  571.3 0.18   12 4.95     2.28     2.45   2.26
1126.59  359.31 1126.59 359.31
  6.95  15.54   6068.   218.2  878.8 0.43  -45 4.12     2.27     2.29   2.32
1160.78  234.72 1160.78 234.72
  2.70  17.25   1260.   215.  1081. 0.16   35 3.28     0.92     0.83   0.90
1198.58  289.39 1198.58 289.39
```

So, this is the coordinate file I'm going to use later, which contains 1008 stars in the cluster.

C. Setting Aperture Size

Back at imexamine, we already know our FWHM is around 2.5. Let's do some radial profiles ('r') and see how the stars look, (Figure 10).

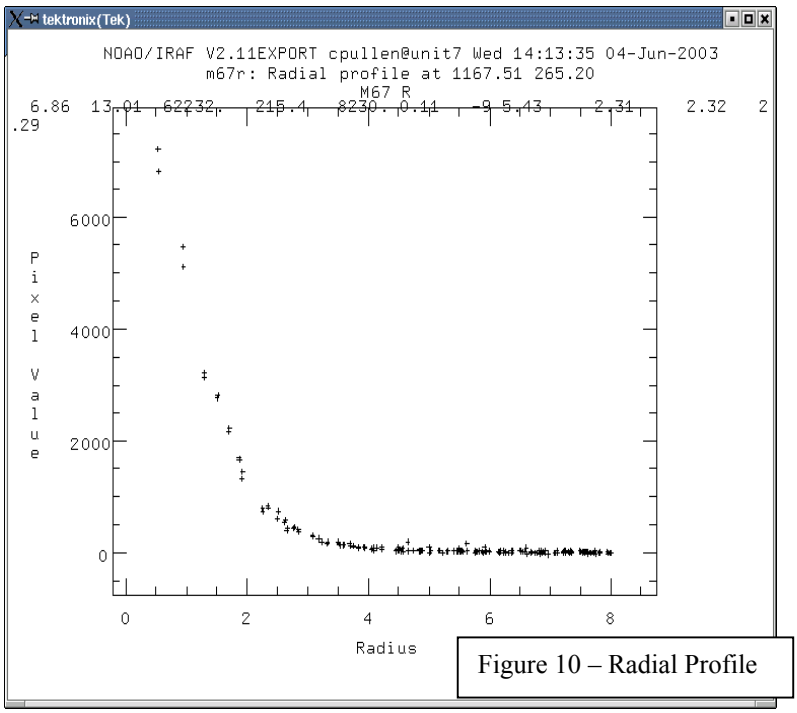


Figure 10 – Radial Profile

The FWHM of that star is about 2.3 pixels. If that is characteristic of the seeing, tracking, and focus for the whole run (check multiple images!) then the rule of thumb is that my aperture radius should be 4 to 5 times that number, or between 9 and 11 pixels. Just to be on the safe side, I'll choose 12.

Want something more scientific? You can do a rate of growth plot as below (Figure 11). Notice that somewhere between 12 and 14 pixels, it mostly peaks out. This is really why I choose 12. Note that in photpar you can set multiple apertures with commas. This set was 2,4,6,8, etc. I then manually did phot on just one star. More on that later. So, at some point, one will see that there is no further significant gain in magnitude - that is the aperture size to use. Massey & Davis (1992) say just use 12 pixels radius as your

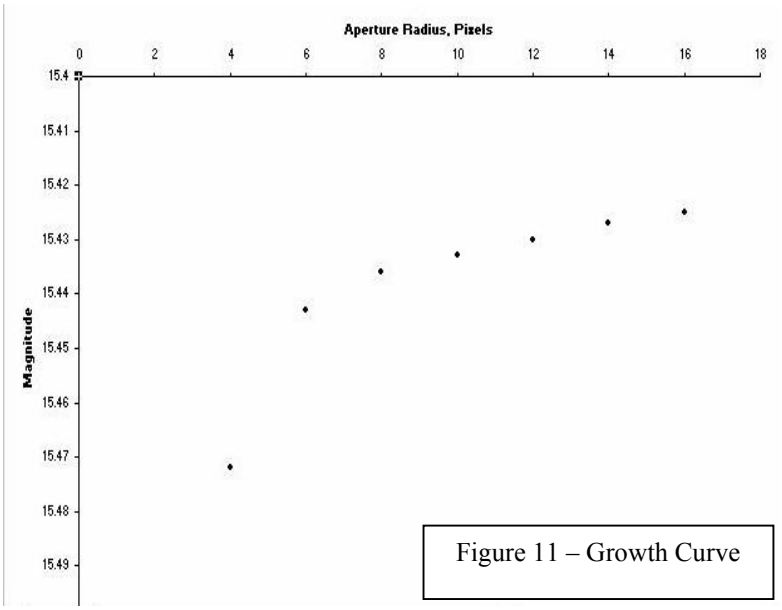


Figure 11 – Growth Curve

aperture size if your images are between 2 and 4 pixels FWHM. Probably not bad advice...

Why not just make it big? You run the risk of getting light from other stars in it, and for single stars, you start to add noise in the form of background light. You also risk getting a bad pixel or cosmic ray hit in your aperture the larger it is as well.

For the beginning of my background annulus, I'm going to choose to start 10 more pixels out from the center, for a number of 12 +10 =22 in radius. I'll add 5 pixels for the outer edge of the background annulus. Again, the idea is to get a good sampling of the background, but not run the risk of any more contamination than necessary, which would happen if you were too close to the center star, or the annulus was too large.

But remember, you must use the same aperture and background annulus for all of your images, or get into complicated and painful aperture corrections. *Remember: The goal is inner peace through IRAF, so keep it simple.*

If you want to see how your choice looks on a radial plot that shows you the boundaries of your aperture and annulus, you can do that with our next IRAF task - phot.

D. Extracting Raw Photometry with phot

Phot is a powerful aperture photometry task. You can run it from the apphot or daophot package. For unknown reasons, Massy and Davis (1992) suggest running it from the daophot package. I would bet that, like rfits and imh files, this is dated advice. Nevertheless*, "disobedience to one's elders can bring bad karma",* so we'll comply.

If you look at the phot parameters you'll see:

```
da> lpar phot
      image = "107*.fts"      Input image(s)
     coords = "107.pam.coo"   Input coordinate list(s) (default: image.coo.?)
     output = "std107.pam.mag" Output photometry file(s) (default: image.mag.
    skyfile = ""              Input sky value file(s)
  (plotfile = "")             Output plot metacode file
   (datapars = "")            Data dependent parameters
 (centerpars = "")            Centering parameters
 (fitskypars = "")            Sky fitting parameters
  (photpars = "")             Photometry parameters
(interactive = no)            Interactive mode ?
  (radplots = no)             Plot the radial profiles?
   (verify = )_..verify)      Verify critical phot parameters ?
   (update = )_.update)       Update critical phot parameters ?
  (verbose = )_.verbose)      Print phot messages ?
 (graphics = )_.graphics)     Graphics device
  (display = )_.display)      Display device
(icommands = "")              Image cursor: [x y wcs] key [cmd]
(gcommands = "")              Graphics cursor: [x y wcs] key [cmd]
     (mode = "ql")
```

It looks deceptively simple. 'image' is our input list, it probably could do multiple fields with the right set up using commas, but I keep it separate. "coords" is our manual or daofind generated coordinate list. 'output' is a text file with the data in it. From 'datapars' to 'photpars' are additional param files

(like in daofind) we'll come back to. 'interactive' allows you to run the program one star at a time. 'radplots' allows you to see how your aperture and background annulus selections look on a radial plot. 'verify' will prompt you for the key parameters for the task. And, if you change them from the command line, it will 'update' the par file with the new values.

Let's use epar to see what is in the hidden pars file. You can epar phot first, then in the field for, say, datapars, type ':e' to get to that par file. Or you could just type 'epar datapar', your choice.

```
PACKAGE = daophot
  TASK = datapars

(scale  =                1.) Image scale in units per pixel
(fwhmpsf=                2.5) FWHM of the PSF in scale units
(emissio=               yes) Features are positive ?
(sigma  =                0.) Standard deviation of background in counts
(datamin=             INDEF) Minimum good data value
(datamax=             INDEF) Maximum good data value
(noise  =           poisson) Noise model
(ccdread=                  ) CCD readout noise image header keyword
(gain   =                  ) CCD gain image header keyword
(readnoi=                0.) CCD readout noise in electrons
(epadu  =                1.) Gain in electrons per count
(exposur=            EXPTIME) Exposure time image header keyword
(airmass=            AIRMASS) Airmass image header keyword
(filter =           FILTERS) Filter image header keyword
(obstime=                 UT) Time of observation image header keyword
(itime  =               30.) Exposure time
(xairmas=     1.7070000171661) Airmass
(ifilter=                 R) Filter
(otime  =         6:06:48.53) Time of observation
(mode   =                 ql)
```

You could use 'datamin' & 'datamax' to exclude stars that are too faint, or too bright. But, we already did this in when we made our coordinate files. The other highlighted fields are header names that will be used to put header information in the outputted data file.

Close 'datapars' with :q, and look at 'centerpars':

```
PACKAGE = daophot
  TASK = centerpars

(calgori=          centroid) Centering algorithm
(cbox   =                5.) Centering box width in scale units
(cthresh=                1.) Centering threshold in sigma above background
(minsnra=                1.) Minimum signal-to-noise ratio for centering algo
(cmaxite=               10) Maximum iterations for centering algorithm
(maxshif=                5.) Maximum center shift in scale units
(clean  =               no) Symmetry clean before centering
(rclean =                1.) Cleaning radius in scale units
(rclip  =               2.) Clipping radius in scale units
(kclean =                3.) K-sigma rejection criterion in skysigma
(mkcente=               no) Mark the computed center
(mode   =               ql)
```

We want to use 'centroid' as our centering method. A 5 pixel box should be able to account for any scatter in our registered positions on the .coo file. You can also set 'maxshif' so that you'll get an error warning if positions shift more than the number of pixels you specify. Save centerpars (':q') and epar fitskypars:

PACKAGE = daophot
  TASK = fitskypars

(salgori= mode) Sky fitting algorithm
(annulus= 22.) Inner radius of sky annulus in scale units
(dannulu= 5.) Width of sky annulus in scale units
(skyvalu= 0.) User sky value
(smaxite= 10) Maximum number of sky fitting iterations
(sloclip= 0.) Lower clipping factor in percent
(shiclip= 0.) Upper clipping factor in percent
(snrejec= 50) Maximum number of sky fitting rejection iteratio
(sloreje= 3.) Lower K-sigma rejection limit in sky sigma
(shireje= 3.) Upper K-sigma rejection limit in sky sigma
(khist = 3.) Half width of histogram in sky sigma
(binsize= 0.10000000149012) Binsize of histogram in sky sigma
(smooth = no) Boxcar smooth the histogram
(rgrow = 0.) Region growing radius in scale units
(mksky = no) Mark sky annuli on the display
(mode = ql)

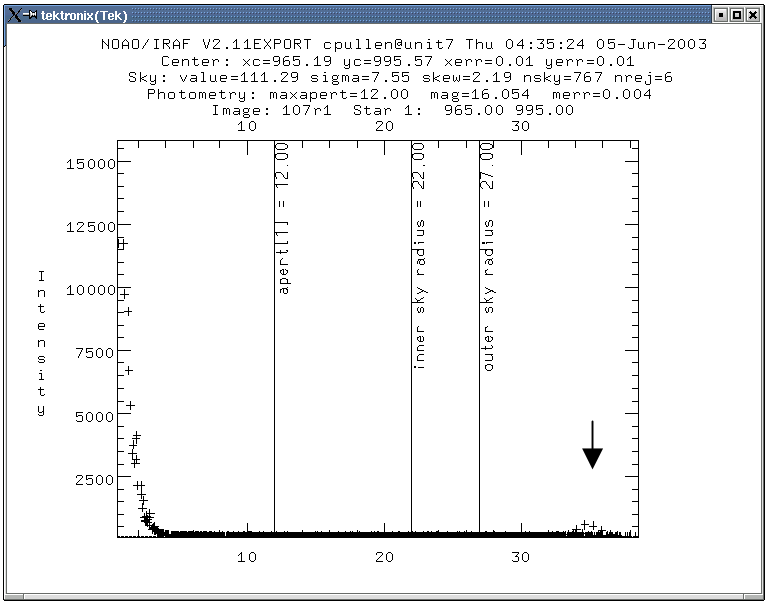


Figure 12 – Radial Profile with Aperture and Annulus. (note PSF of adjacent star)

Choose 'mode' for your 'salgori'. Here is where we set where the background annulus starts, and how wide it is. Finally, lets look at 'photpars'

PACKAGE = daophot
  TASK = photpars

(weighti= constant) Photometric weighting scheme
(apertur= 12.) List of aperture radii in scale units
(zmag = 25.) Zero point of magnitude scale
(mkapert= no) Draw apertures on the display
(mode = ql)

'weighti' is always constant in daophot. 'apertur' is where you specify your aperture(s). If you want multiple, use commas ('10,12,14'). 'zmag' is a dummy zero point. It will be modified as part of the standardization we will be doing later. It really should be zero, as you would then have true instrumental magnitudes. But, these are all negative numbers, so it might cause math problems for IRAF. Leave it at the default.

So, now the big moment: Let's run phot, first in "manual" mode. Change phot pars to interactive with rplot enabled. Load the image in the display, and type 'phot imagename'. Once you confirm the parameters, you'll get a graphics cursor (blinking circle) on your display. Center it on a star, and hit the space bar. You'll get this radial profile (Figure 12), with your aperture and annulus displayed, as well as this output on your screen:

da> phot 107r1
Input coordinate list(s) (default: image.coo.?) (104.pam.coo): 107.pam.coo
Output photometry file(s) (default: image.mag.?) (104.pam.mag): 107.mag.manual
Warning: Graphics overlay not available for display device.
107r1 965.19 995.57 111.2863 16.054 ok

Ignore the "Warning", it works fine!

There is a lot more information in the data file (107.mag.manual) lets look at it with an edit command (it's in the Appendix). The first section is all your parameters. The next tells you what all the fields are. The final section is your actual data. See the "noError"? That tells you that IRAF didn't have any situations occur out of norms.

Now, lets get automated! Change interactive and rplots back to "no" and lets do the standards.

```
da> phot
Input image(s) (107*.fts):
Input coordinate list(s) (default: image.coo.?) (107.pam.coo):
Output photometry file(s) (default: image.mag.?) (std107.pam.mag): 107.mag.example
Centering algorithm (centroid) (CR or value):
      New centering algorithm: centroid
Centering box width in scale units (5.) (CR or value):
      New centering box width: 5. scale units  5. pixels
Sky fitting algorithm (mode) (CR or value):
      Sky fitting algorithm: mode
Inner radius of sky annulus in scale units (20.) (CR or value):
      New inner radius of sky annulus: 20. scale units 20. pixels
Width of the sky annulus in scale units (5.) (CR or value):
      New width of the sky annulus: 5. scale units 5. pixels
File/list of aperture radii in scale units (12) (CR or value):
      Aperture radius 1: 12. scale units 12. pixels
Minimum good data value (INDEF) (CR or value):
      New minimum good data value: INDEF counts
Maximum good data value (INDEF) (CR or value):
107b1.fts   1518.86  1108.62  56.14318   18.654  ok
107b1.fts   1025.16  1765.04  54.38914   18.256  ok
107b1.fts    965.30   995.60  54.86342   18.309  ok
107b1.fts    920.85   974.61  55.01133   20.204  ok
107b1.fts    934.42   449.73  54.79597   17.394  ok
107b1.fts    880.01  1111.66   55.1084   17.602  ok
...
```

Do the same with the other field, specifying a different .mag file name or append it to your other file with '>>107.pam.mag'. Edit out the second set of parameters and field identifiers, so that you have one file full of just the phot output of your standards.

Since the .mag files can be unwieldy, IRAF gives you a tool called 'txdump' to parse them. Here is an example to pull just select information out of a .mag file:

```
da> txdump 104.pam.mag image,id,xcenter,ycenter,ifilter,xairmass,mag,merr yes

104b1.fts  1  839.036  940.677  B  1.409  18.827  0.008
104b1.fts  2  748.371  1093.615  B  1.409  19.518  0.013
104b1.fts  3  488.016  877.080  B  1.409  21.068  0.045
104b1.fts  4  407.867  875.756  B  1.409  18.273  0.006
104b1.fts  5  383.930  961.248  B  1.409  21.661  0.080
104b1.fts  6  348.996  928.250  B  1.409  20.893  0.037
...
```

If you wanted to make an output file that you could put into Excel, you can txdump to a file:

```
da> txdump 104.pam.mag >104mag.dat
Fields to be extracted (image,id,xcenter,ycenter,ifilter,xairmass,mag,merr):
Boolean expression for record selection (yes):
da>
```

Remember the "NoError" phrase? If you want to be sure you extract only data that in fact has "NoError", use the following boolean expression:

```
da> txdump *.pam.mag > 104.mag.dat
Fields to be extracted (image,id,xcenter,ycenter,ifilter,xairmass,mag,merr):
Boolean expression for record selection (yes): perror!="No_error"
104b1.fts  1  839.036  940.677  B  1.409  18.845  0.006
104b1.fts  2  748.371  1093.615  B  1.409  19.537  0.009
104b1.fts  3  488.016  877.080  B  1.409  25.217  0.921
104b1.fts  4  407.867  875.756  B  1.409  18.293  0.005
104b1.fts  5  383.930  961.248  B  1.409  21.732  0.039
...
```

Now, if all you wanted to do was differential photometry, without transforming to the standard system, you can import your data into Excel or use a PERL program to do the subtraction, and leave IRAF behind. However, since the goal of my project was to work on the standard system, I'll walk you though those steps next.

V. STANDARD SYSTEM CORRECTION

Disciples as numerous as grains of sand in the River Ganges, not one has gained enlightenment; they err in seeking it as a path taught by others. To eliminate form and eradicate its traces, make utmost effort and strive diligently to walk in nothingness.

Tung-shan Liang-chieh (807-869)

If you are not clear on what it means to put your data on the standard Johnson-Cousins BVRI system refer to some of the reference links. In brief summary, the idea is to find out from our standard fields how both color and magnitude are affected by airmass, and to calculate the actual zero point for each color and/or color index. This is why we took images of standard fields at different airmasses. IRAF can determine extinction and transformation coefficients for you, then apply them to that massive m67.mag file. But, like all things on the path to Nirvana, it will take a bit of work.

In summary we will:

- Make an Image Set
- Make an Observations File
- Make a Configuration File
- Determine by Interactive Fitting our Transformation and Extinction Coefficients
- Check that the Coefficients can Back Calculate our Standard Star Values

A. Making an Image Set

We'll be using the photcal package, found in noao.digiphot, so load that. Our first step is to tell IRAF what images have standard star data. We can do that with 'mkimset'.
The par file is:

```
PACKAGE = photcal
  TASK = mkimsets
imlist  =                The input image list
idfilter=                The list of filter ids
imsets  =                 The output image set file
(imobspa=                 ) The output image observing parameters file
(input  =          photfiles) The source of the input image list
(filter =                ) The filter keyword
(fields =                 ) Additional image list fields
(sort   =                ) The image list field to be sorted on
(edit   =               yes) Edit the input image list before grouping
(rename =                yes) Prompt the user for image set names
(review =               yes) Review the image set file with the editor
(list   =               )
(mode   =                ql)
```

However, it may be easier to simply make it with a text editor. Here is the standard star imset I used for my project:

```
ph> type stdimset
104_1 : 104b1.fts 104i1.fts 104r1.fts
104_2 : 104b2.fts 104i2.fts 104r2.fts
107_1 : 107b1.fts 107i1.fts 107r1.fts
107_2 : 107b2.fts 107i2.fts 107r2.fts
107_3 : 107b3.fts 107i3.fts 107r3.fts
```

As can be seen, all an imset does is tell IRAF that there are two observations of the SA 104 field, and three of the SA107 field, with what image names are in those observations. Note, rather than use 'edit', for a quick look at a file in the IRAF window, I used 'type'.

B. Making a Standard Star Observation File

'mknobsfile' is the task that makes a file of our standard observations, as well as creates format files to help IRAF find the right information the later tasks will need. **Note!** The command is mk**n**obsfile, not *mkobsfile*! *mkobsfile* is a different command! Look at the help file to see the difference.

The mknobsfile par file is :

```
PACKAGE = photcal
  TASK = mknobsfile

photfile=        std.pam.mag  The input list of APPHOT/DAOPHOT databases
idfilter=            B,I,R  The list of filter ids
imsets  =          stdimset  The input image set file
observat=        std.pam.obs  The output observations file
(obspara=                  ) The input observing parameters file
(obscolu=            2 3 4 5) The format of obsparams
(minmage=              0.001) The minimum error magnitude
(shifts =                  ) The input x and y coordinate shifts file
(apercor=                  ) The input aperture corrections file
(apertur=                  1) The aperture number of the extracted magnitude
(toleran=                 5.) The tolerance in pixels for position matching
(allfilt=                yes) Output only objects matched in all filters
(verify =                 no) Verify interactive user input ?
(verbose=                yes) Print status, warning and error messages ?
(mode   =                 ql)
```

As usual, 'photfile' is your input file name. Note that I combined the two separate .mag files for SA104 and SA107. 'idfilter' are your filter names. 'stdimset' is the name of the file made in the previous step. 'obscolu' are the columns of relevant data in the input file, which if IRAF made the .mag file, should be default. Let's run mknobsfile and see what happens:

```
ph> mknobsfile
The input list of APPHOT/DAOPHOT databases (std.pam.mag): stdcombo.pam.mag
The list of filter ids (B,I,R):
The input image set file (stdimset):
The output observations file (std.pam.obs.example): std.pam.obs

Observations file: std.pam.obs
      Image set: 104_1  6 stars written to the observations file
      Image set: 104_2  6 stars written to the observations file
      Image set: 107_1  18 stars written to the observations file
      Image set: 107_2  18 stars written to the observations file
      Image set: 107_3  18 stars written to the observations file
```

If you look at your directory, you'll see that a two new files were created:

```
ph> dir
104.pam.coo        107.pam.coo        107r3.fts          m67i.fts
104.pam.coo~       107.pam.mag        Apr01.obsfile      m67r.fts
104.pam.mag        107b1.fts          AprLandolt.dat     std.pam.invertfit
104b1.fts          107b2.fts          aperturegrowth.txt  std.pam.obs
104b2.fts          107b3.fts          aperturegrowth.txt  stdcombo.pam.mag
104i1.fts          107i1.fts          fAprLandolt.dat    stdimset
104i2.fts          107i2.fts          fstd.pam.obs.dat   tAprLandolt.dat
104r1.fts          107i3.fts          m67.coo.example3
104r2.fts          107r1.fts          m67.mag
107.mag.manual     107r2.fts          m67b.fts
```

Looking at a bit of the .obs file,

```
ph> type std.pam.obs

# FIELD       FILTER         OTIME AIRMASS  XCENTER   YCENTER     MAG   MERR

104_1-1       B          3:09:02.9  1.409   839.036   940.677  18.827  0.008
*             I          3:14:50.0  1.387   839.282   940.609  16.451  0.004
*             R          3:04:43.5  1.431   839.065   940.633  16.918  0.006
104_1-2       B          3:09:02.9  1.409   748.371  1093.615  19.513  0.012
*             I         3:14:50.0  1.387   748.586  1093.570  17.254  0.009
*             R         3:04:43.5  1.431   748.392  1093.597  17.633  0.010
...
```

There is a fatal problem here, which is subtle and will drive you past the point of inner calm if you don't correct it. See the star names (104_1-1, 104_1-2, etc.)? IRAF cannot match these to the Landolt catalog. As you'll remember, you choose which stars to use, but they are named something like 104_350. So, you need to match up the proper names with the IRAF name for the individual star. Much drudgery with a text editor awaits you. But, remember there is serenity in simple labor. Come back after you've fixed the star names, and perhaps taken a walk to work off your unseemly lack of inner calm.

It should be clear by now that IRAF will protect you from yourself to a large degree. It will not tolerate errors in file format. If it doesn't add up, it will fault. Now, this trait doesn't protect you from giving it wrong information in the right format, but it is helpful to think of IRAF as a protective Godess, as it faults, and faults, and faults until you get all these little errors fixed. At least it never holds a grudge... not even the Greeks could say that of their Godesses!

If you did the same fields, night after night, you would still need to hand edit the .obs file from each night to correct the star names. This can cause karmic distress! Now, those willing to try to cut corners on the way to Nirvana may be tempted to use Excel to import the column with the correct names from a previous night's file into the latest file that needs correcting. Go ahead, make IRAF's day! Excel will damage the file so that it won't work later by shuffling columns. Great karmic distress will ensue.

The problem is that you can save a text file in Excel only as a comma or tab delimited file. But, IRAF uses white space as the column delimiter. Use commas, and you can spend the rest of eternity hand editing them out. Use tabs, and there will be problems reading the file. *Remember, the "Great Satan of Redmond" brought Excel into the world, and there are those who believe He is the AntiChrist...*

If in fact you need to use the same fields, night after night, which is where IRAF really shines, you could write a PERL or other script program to replace 104_1-1 with 104_350 wherever it finds it in the .obs file. This is probably the best method for returning a sense of calm to your inner core.

We expected to make std.pam.obs, but what is this fstd.pam.obs.dat file?

```
ph> type fstd.pam.obs.dat
# Declare the observations file variables

observations

TB          3          # time of observation in filter B
XB          4          # airmass in filter B
xB          5          # x coordinate in filter B
yB          6          # y coordinate in filter B
mB          7          # instrumental magnitude in filter B
error(mB)   8          # magnitude error in filter B

TI          10         # time of observation in filter I
XI          11         # airmass in filter I
xI          12         # x coordinate in filter I
yI          13         # y coordinate in filter I
mI          14         # instrumental magnitude in filter I
error(mI)   15         # magnitude error in filter I

TR          17         # time of observation in filter R
XR          18         # airmass in filter R
xR          19         # x coordinate in filter R
yR          20         # y coordinate in filter R
mR          21         # instrumental magnitude in filter R
error(mR)   22         # magnitude error in filter R
```

As you can see, the 'f' means "format". It tells IRAF what the fields in the .mag file are.

C. Making Configuration Files

Next comes a step that caused a lot of problems for me early on, so there was much inner growth associated with it. You need to tell IRAF which catalog to use, and what the format of that catalog is. You also have to tell IRAF what the transformation equations are that you want to use. Finely, you have to tell IRAF how to interpret your .mag files. If you are able to use Landolt (1992) life is pretty simple. The catalog is already installed, as are its format and transformation files. As would be seen in the 'mkconfig' par file, respectively, those are:

```
catalog = photcal$catalogs/fnlandolt.dat      # the path is different, it isn't in your working directory
observations = fstds.pam.obs.dat              # made with 'mknobsfile in the previous step
transform = tlandolt.dat
```

However, in my project, I had a problem. I have B, R, and I data. For the CMD, I was going to use R vs B-R. However, there is no data in Landolt 1992 for B-R. My options are V, B-V, V-R, R-I, and V-I. So, I had to calculate R and B-R from the available Landolt data, and make my own catalog, along with the catalog format files. IRAF helps you with this, with the 'mkcatalog' task. However, it was a real pain. Upon request, the instructor provided me with a catalog along with the format and transformation files for that catalog (Gay 2003). We'll continue on as if I was working with the onboard catalog.

Looking at the par file for 'mkconfig', you can see it is straightforward to use, once all the catalog and fomat files are right:

```
PACKAGE = photcal
  TASK = mkconfig

config  =       std.pam.cfg  The new configuration file
catalog =    fAprLandolt.dat  The source of the catalog format specification
observat=    fstd.pam.obs.dat  The source of the observations file format speci
transfor=    tAprLandolt.dat  The source of the transformation equations
(templat=                  ) An existing template configuration file
(catdir =         )_.catdir) The standard star catalog directory
(verify =               no) Verify each new entry
(edit   =              yes) Edit the new configuration file
(check  =              yes) Check the configuration file
(verbose=               no) Verbose output
(mode   =               ql)
```

Running mkconfig, I get the following in an editor (EMACS) window. This is IRAF's way to let me look at the file and make any edits now.

```
#  Declare the new Landolt UBVRI standards catalog variables

catalog

BR         2                    # BR color
R          3                    # R magnitude
RI         4                   # RI color
error(BR)  5                    # the BR color error
error(R) 6                      # the R magnitude error
error(RI) 7                     # the RI color error
```

```
# Declare the observations file variables

observations

TB          3          # time of observation in filter B
XB          4          # airmass in filter B
xB          5          # x coordinate in filter B
yB          6          # y coordinate in filter B
mB          7          # instrumental magnitude in filter B
error(mB)   8          # magnitude error in filter B

TI          10         # time of observation in filter I
XI          11         # airmass in filter I
xI          12         # x coordinate in filter I
yI          13         # y coordinate in filter I
mI          14         # instrumental magnitude in filter I
error(mI)   15         # magnitude error in filter I

TR          17         # time of observation in filter R
XR          18         # airmass in filter R
xR          19         # x coordinate in filter R
yR          20         # y coordinate in filter R
mR          21         # instrumental magnitude in filter R
error(mR)   22         # magnitude error in filter R

# Sample transformation section for the Landolt UBVRI system

transformation

fit   b1=0.0, b2=0.35, b3=0.000
BFIT : mB = (BR + R) + b1 + b2 * XB + b3 * BR

fit   r1=0.0, r2=0.0, r3=0.000
RFIT : mR = R  + r1 + r2 * XR + r3 * BR

fit   i1=0.0, i2=0.00, i3=0.000
IFIT : mI = (R - RI) + i1 + i2 * XI + i3 * RI
```

For the transformation equations, the numbers after 'fit' mean as follows:

1 = zero point adjustment coefficient
2= extinction coefficient
3= color transformation coefficient

These are used as a "first approximation" by IRAF when it attempts to fit the transformation plots in the next step. They can be set to zero in most cases. Note also in the transformation equations that "R-I" is denoted as 'RI' etc. This is a syntax issue with IRAF.

So, if everything is to your liking, save the file and exit the editor. I got:

```
ph> mkconfig
The new configuration file (std.pam.cfg):
The source of the catalog format specification (fAprLandolt.dat):
The source of the observations file format specification (fstd.pam.obs.dat):
The source of the transformation equations (tAprLandolt.dat):

** Beginning of compilation **
** End of compilation **
```

```
Catalog input variables        = 6
First catalog column           = 2
Last catalog column            = 7
Observational input variables  = 18
First observational column     = 3
Last observational column      = 22
Fitting parameters             = 9
Constant parameters            = 0
Auxiliary (set) equations      = 0
Transformation equations       = 3
Warnings                       = 0
Errors                         = 0
```

You'll know all is well if 'Warnings' and 'Errors' is zero. If not, go to the help file for mkconfig to learn what they mean and try to fix the problem. In general, an error or warning means that something in one of the three input files to mkconfig is not in exactly the right format. Remember, GIGO ("Garbage-In, Garbage-Out").

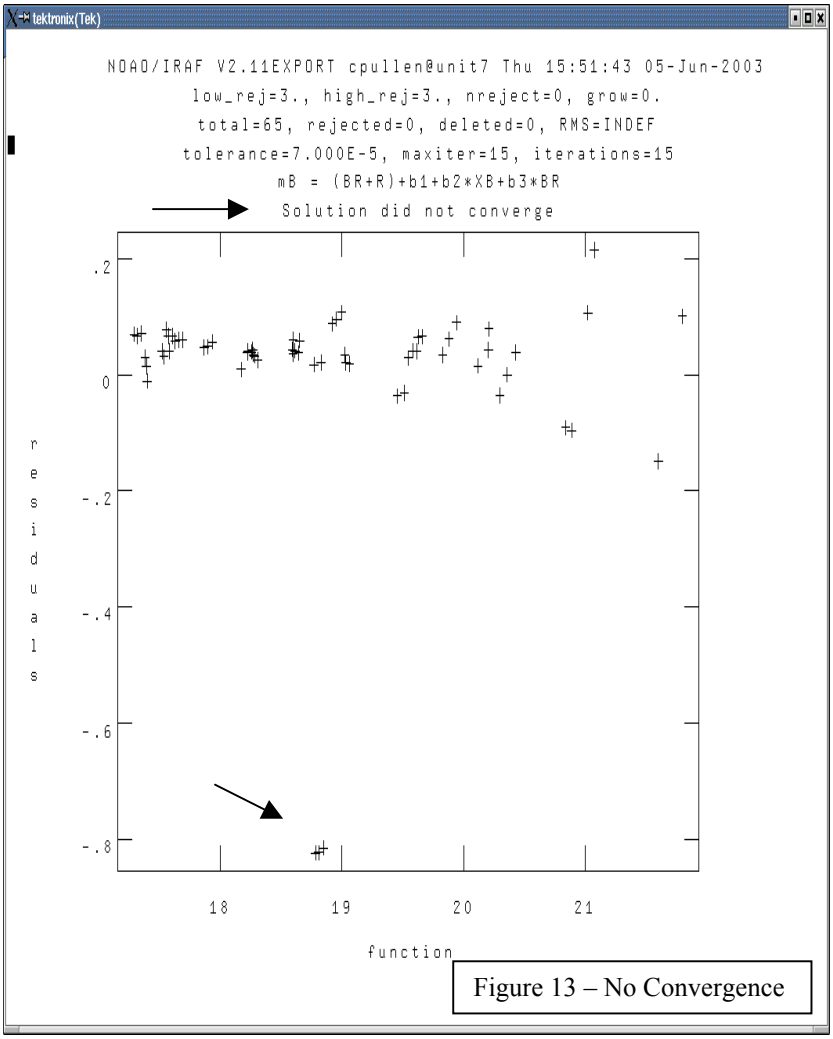


Figure 13 – No Convergence

D. Fitting the Transformation Plots

Now comes the fun part, seeing how good your standards data really is, and generating the transformation, zero point, and extinction coefficients using the task 'fitparams'. Let's look at the par file first:

```
PACKAGE = photcal
   TASK = fitparams

observat=     std.pam.obs  List of observations files
catalogs=       AprLandolt.dat  List of standard catalog files
config  =         std.pam.cfg  Configuration file
paramete=         std.pam.ans  Output parameters file
(weighti=          photometric) Weighting type
(uniform,photometric,equations)
(addscat=                 yes) Add a scatter term to the weights ?
(toleran=   3.0000000000000E-5) Fit convergence tolerance
(maxiter=                  15) Maximum number of fit iterations
(nreject=                   0) Number of rejection iterations
(low_rej=                  3.) Low sigma rejection factor
(high_re=                  3.) High sigma rejection factor
(grow   =                  0.) Rejection growing radius
(interac=                 yes) Solve fit interactively ?
(logfile=             fitlog.dat) Output log file
(log_unm=                  yes) Log any unmatched stars ?
(log_fit=                 yes) Log the fit parameters and statistics
?
(log_res=                  yes) Log the results ?
(catdir =           )_.catdir) The standard star catalog directory
(graphic=            stdgraph) Output graphics device
(cursor =                    ) Graphics cursor input
(mode   =                  ql)
```

Here you name all the files you have made that are needed for the task. 'weighti' should be 'photometric'. We'll start with the default 'toleran' as we can interactively change that as needed. We want to solve the fit interactively, and log errors and statistics in the logfile fitlog.dat. Lets run it!

```
ph> fitparams
List of observations files (std.pam.obs):
List of standard catalog files (AprLandolt.dat):
Configuration file (std.pam.cfg):
Output parameters file (std.pam.ans):
```

First you get an interactive graph (Figure 14). Notice the ominous phrase "Solution did not converge". This is IRAF's version of "I can't let you do that, Dave" (HAL 9000 in “2001, A Space Odyssey”). What it really means is that the solution doesn't fit to the tolerances you specified or accepted as the defaults. Notice that you have three points at the bottom left part of the plot that are way out of the bounds of the rest of the points. These are stars that didn't fit well. Perhaps they are too faint, or the apertures are contaminated. Let’s get rid of them and try again.

Put your cursor on them one at a time, and type 'd'. This will change the '+' to a '*' meaning they have been removed from the calculation. Try the fit again by typing 'f'. That does it. Type 'q' to exit this plot, accept the solution with a 'yes', then 'n' for the next color. Continue until you are done with all of them.

As an example of when good stars go bad, look at Figure 14. It shows another case of non-convergence. My R and I fit did not work, even when I deleted the stars at the bottom left. I had to change the tolerance to ':tolerance 1.8e-4' before it would converge. Clearly, there is a problem here, and you can see that what should be linear is in fact curved - a sure sign of trouble. So, I'd use R as a function of R-I coefficients with a great deal of skepticism. This really means that, for whatever reason, it's hard to put data from this camera and filters on the standard system using I data.

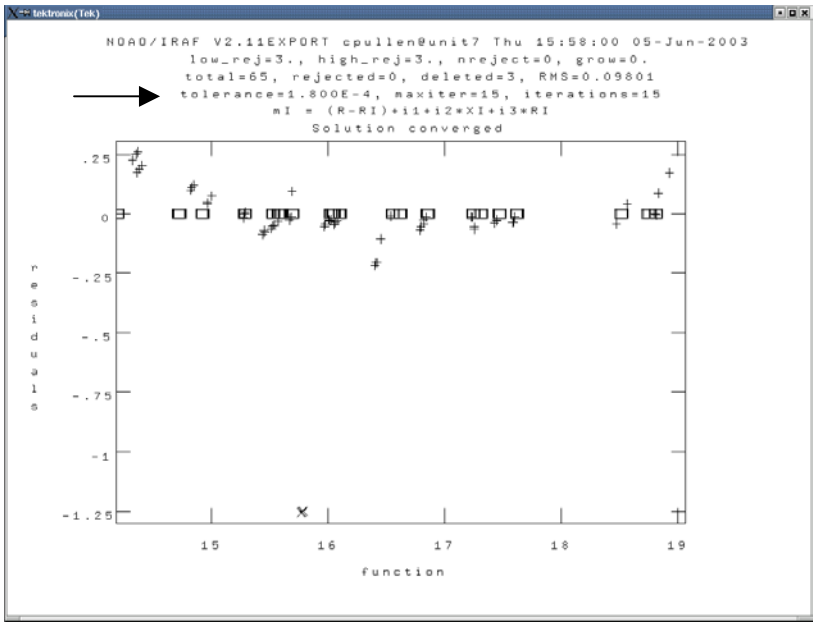


Figure 14– note display problem, strange squares

Type 'q', then 'q' again to exit fitparams. Congratulations, you now have coefficients in your .ans file. Look in the Appendix for them, and be satisfied!

E. Back checking your Work

How good do these coefficients really work? IRAF can help you find out with a task in photcal called 'invertfit' which will calculate the values of your standard stars from your coefficients so you can see how well they work. Look at the par file:

```
PACKAGE = photcal
  TASK = invertfit

observat=        std.pam.obs  List of observations files
config  =        std.pam.cfg  Configuration file
paramete=        std.pam.ans  Fitted parameters file
```

```
calib   =    std.pam.invertfit  Output calibrated standard indices file
(catalog=                      ) List of standard catalog files
(errors =            obserrors) Error computation type (undefined,obserrors,equa
(objects=                 all) Objects to be fit (all,program,standards)
(print  =                      ) Optional list of variables to print
(format =                      ) Optional output format string
(append =                   no) Append output to an
existing file ?
(catdir =            )_.catdir) The standard star catalog
directory
(mode   =                   ql)
```

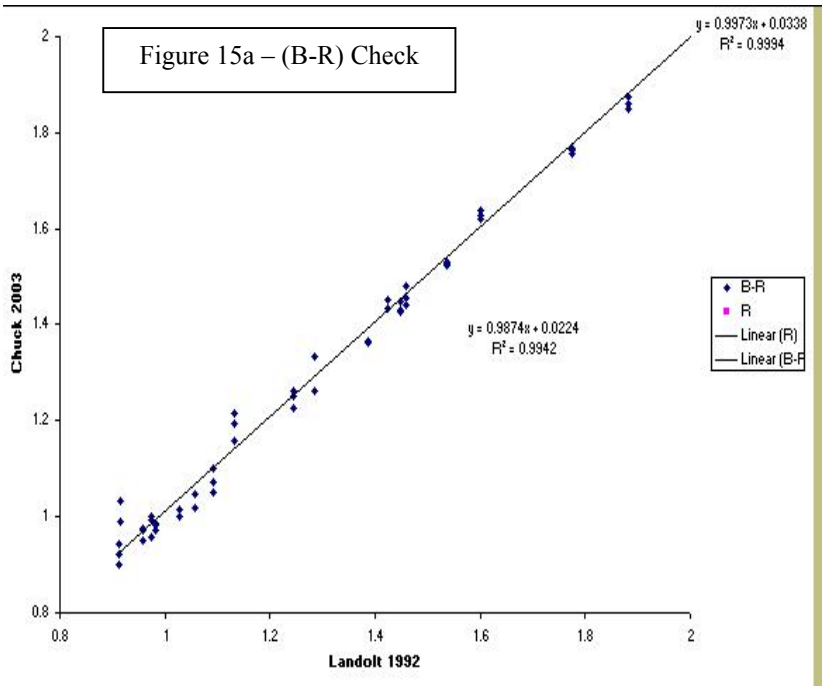


Figure 15a – (B-R) Check

It's pretty self-explanatory by this time. Let's run it, and see what happens.

```
ph> invertfit
List of observations files (std.pam.obs):
Configuration file (std.pam.cfg):
Fitted parameters file (std.pam.ans):
Output calibrated standard indices file
(std.pam.invertfit):
```

Taking a look at my output file:

```
ph> type std.pam.invertfit

# Thu 16:17:02 05-Jun-2003
# List of observations files:
#              std.pam.obs
# Config:      std.pam.cfg
# Parameters:  std.pam.ans
#
# Computed indices for program and standard objects
#
# Columns:
#      1      object id
#      2      BR
#      3      error(BR)
#      4      R
#      5      error(R)
#      6      RI
#      7      error(RI)


104_350   1.047  0.011  13.244 0.006  0.472
0.009
104_470   1.014  0.018  13.960 0.010  0.367
0.016
104_364   0.989  0.064  15.492 0.038  0.200
0.064
104_366   1.361  0.008  12.407 0.004  0.522
0.006
104_479   1.566  0.102  15.553 0.042  0.705
0.063
104_367   0.888  0.058  15.450 0.035  0.285
0.058
...
```

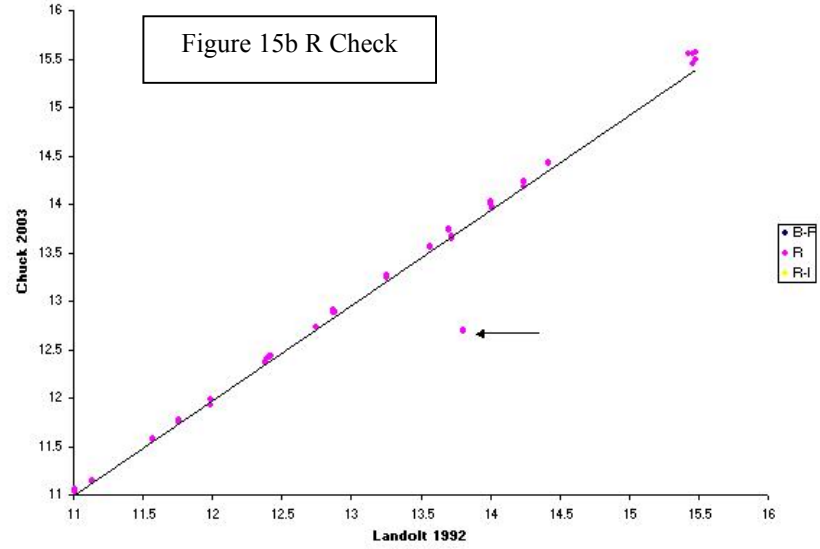


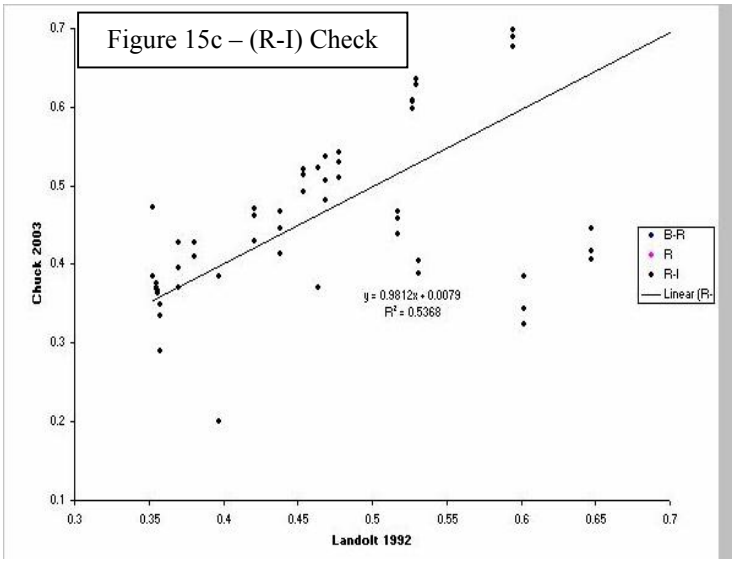
Figure 15b R Check

I can see what my calculated values are. I can check for fit by inspection with my catalog file, such as:

```
ph> type AprLandolt.dat
```

#ID BR R RI BRerr Rerr RIerr

104_350 1.056 13.251 0.353 0.0067 0.0075 0.0045
104_470 1.027 14.015 0.356 0.0225 0.0254 0.0035
104_364 0.915 15.485 0.397 0.0573 0.0241 0.041
104_366 1.387 12.391 0.464 0 0 0
104_479 1.928 15.43 0.607 0.0304 0.0367 0.0035
104_367 1.021 15.462 0.296 0.0389 0.0432 0.0042



But, this is extremely laborious for so many standards. The easier way is to graph Landolt's values vs. my values and see how well it fits by linear regression. This is, in fact, easiest to do in Excel (Figures 15a,b,&c).

As can be seen, there is pretty good fit for the R data, with only one point that is bad (107_611). B-R has several points that are not great, (104_368, 1-4_367, 104_479 and 107_611). R-I is just bad all over. There is a choice here. Were these some of the points that were discarded during 'fitparams'? Check your log file. If so, then look at the images and see why they are in error. Catalog entry wrong? Not a good choice from Landolt 1992 because of too few observations? Is there a contaminated aperture or background annulus? Try to understand why they are unusable. If you are really walking down the path of serenity, you will want to go back and redo you transformation and extinction coefficients without these stars in the mix. Or, you might decide that their influence is not worth the effort. As with all things, the choice is yours, choose wisely!

VI.THE FINISHED PRODUCT

Luke said: "I'm not afraid, Master Yoda."
Yoda replied: "You will be!"

Star Wars Episode IV - Return of the Jedi

Now that we have extracted our M67 photometry, and have transformation and extinction coefficients, it is time for the last step - converting that data to the standard system. We will use 'invertfit' for this task, as we did with our standards. However, you'll need to go back and make an imset, .obs, and .cfg file for M67, exactly as you did for your standards. Apply 'invertfit' as before, and your output file will be your data on the standard system. Something like:

```
# Thu 18:05:48 05-Jun-2003
# List of observations files:
#                   m67.obs
# Config: m67.cfg
# Parameters:       std.pam.ans
#
# Computed indices for program and standard objects
#
# Columns:
#         1         object id
#         2         BR
```

```
#       3       error(BR)
#       4       R
#       5       error(R)
#       6       RI
#       7       error(RI)


m67_1-1   INDEF   INDEF   INDEF   INDEF   INDEF   INDEF
m67_1-2   INDEF   INDEF   INDEF   INDEF   INDEF   INDEF
m67_1-3   INDEF   INDEF   INDEF   INDEF   INDEF   INDEF
m67_1-4   INDEF   INDEF   INDEF   INDEF   INDEF   INDEF
m67_1-5   INDEF   INDEF   INDEF   INDEF   INDEF   INDEF
m67_1-6   INDEF   INDEF   INDEF   INDEF   INDEF   INDEF
m67_1-7   1.488   0.005   12.001  0.002   0.360   0.003
m67_1-8   1.296   0.007   12.690  0.003   0.522   0.004
m67_1-9   INDEF   INDEF   INDEF   INDEF   INDEF   INDEF
m67_1-10  1.122   0.054   15.625  0.031   0.646   0.044
m67_1-11  0.908   0.007   12.870  0.004   0.364   0.006
m67_1-12  0.895   0.010   13.445  0.005   0.369   0.008
m67_1-13  1.078   0.028   14.796  0.016   0.388   0.024
m67_1-14  1.234   0.035   14.963  0.018   0.419   0.027
m67_1-15  1.028   0.011   13.601  0.006   0.400   0.009
m67_1-16  1.168   0.025   14.617  0.013   0.452   0.020
m67_1-17  0.968   0.047   15.470  0.029   0.504   0.042
```

Notice all the INDEF notations? That means that during the photometry, IRAF was not happy with the results, and therefore did not print them. Out of 1003 stars chosen with daofind, only 18 had one or more INDEF magnitude or color indexes.

Now, to plot your CMD (remember - the goal of the exercise?). You can import this file into Excel and plot from there. I prefer GNUPLOT, so the file needs reshuffling to the format B-R vs R (x vs y) in two columns. I did this shuffling in Excel, and deleted the INDEF data because it will fault GNUPLOT. The resulting plot is Figure 16. Note the axes are V and B-V as I transformed them because I didn't have any V data and needed them that way in a CMD. Forget about it at this point!

The main sequence is clearly visible, although there seem to be a lot of stars all over the place. One reason is that foreground stars have not been removed. Another reason is that there may be some points that are so far out of reality due to the crowded field that the photometry is suspect. One will have to go though each point (all 990) and decide if they belong in the plot, or are suffering from contamination or other problems before the final product is really ready for prime time. But, that will be the subject of another paper someday!

One minute of sitting, one inch of Buddha.
Like lightning all thoughts come and pass.
Just once look into your mind-depths:
Nothing else has ever been.

Manzan (1649-1709)

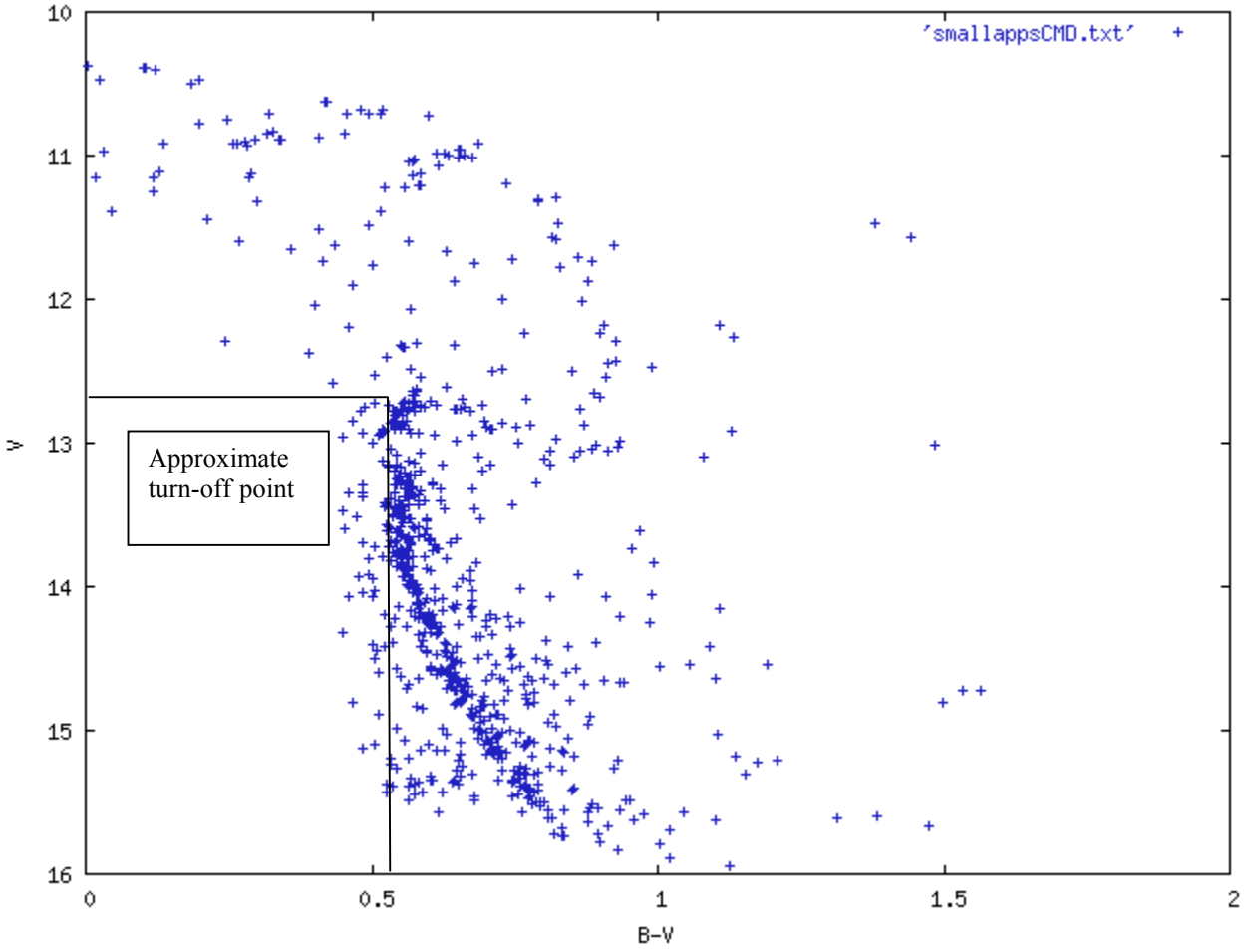


Figure 16 – CMD of M67

VII. ACKNOWLEDGEMENTS

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Acknowledgement is also given to years of photometric help, including IRAF and LINUX assistance, by Dr. Arne A. Henden, Dr. Dirk Terrel, Gary Billings, and Aaron Price. Tim Hager has also provided critical start up advise with IRAF. Of course, a task of this size could not have been done without the support of the author's wife and child.

VIII . RESOURCES

- IRAF Tutorials and User Manuals: http://iraf.noao.edu/iraf/web/docs/docmain.html and sub pages
- SAO DS9 Viewer: http://hea-www.harvard.edu/RD/ds9/
- The Random Factory: http://www.randomfactory.com.
- WCS-Tools: http://tdc-www.harvard.edu/software/wcstools/
- Xephem: http://www.clearskyinstitute.com/xephem/
- Mira Software: http://www.axres.com
- Online version of Landolt –92 with finder charts: http://www.ls.eso.org/lasilla/Telescopes/2p2T/Landolt/
- Close-up finder charts for selected Landolt stars: http://www.ucolick.org/~mountain/mhtechdocs/techdocs/standards/
- Excellent tutorial on photometry: http://observatory.ou.edu/book4512.html.
- "AAVSO Guide to CCD Photometry": http://www.aavso.org/ccd/manual/.
- "Getting Started in CCD Photometry": http://www.aavso.org/committees/ccdnew.shtml.
- "Astronomical Photometry", Henden and Kaitchuck, 1992: http://www.willbell.com/photo/photo4.htm. (It's old, and deals with single channel photo-multiplier based photometers. But, the theory and applications are exactly the same as a CCD)

XI. REFERENCES

Berry, R. & Burnell, J.; 2000 "Handbook of Astronomical Image Processing", Willman Bell Publishers

Billings, G. 2003; Personal Communication

Gay, P. 2003 - Personal Communication

Hager, T.; 2002, Personal Communication

Landolt, A._ 1992 AJ **104** 340

Massy, P. & Davis, L.E; 1992 "A User's Guide to Stellar CCD Photometry with IRAF", NOAO

Massy, P. ; 1997 "A User's Guide to CCD Reductions with IRAF", NOAO

Wells, L.A; Bell, D.J" "Cleaning Images of Bad Pixels and Cosmic Rays Using IRAF", NOAO

Zen Quotes from http://:www.dailyzen.com

Cover Art Work from http://www.thegalleryofchina.com/lotuspainting9.html

X. APENDIX

LOGIN.CL

```
# LOGIN.CL -- User login file for the IRAF command language.

# Identify login.cl version (checked in images.cl).
if (defpar ("logver"))
   logver = "IRAF V2.11 May 1997"

set         home                = "/home/cpullen/"
set         imdir               = "./pix/"
set         uparm               = "home$uparm/"
set         userid              = "cpullen"

# Set the terminal type.
if (envget("TERM") == "sun") {
   if (!access (".hushiraf"))
            print "setting terminal type to gterm..."
   stty gterm
} else {
   if (!access (".hushiraf"))
            print "setting terminal type to xterm..."
   stty xterm
}

# Uncomment and edit to change the defaults.
set         editor              = emacs
#set        printer             = lw
set         stdimage  = imt2048
set         stdimcur  = stdimage
#set        stdplot             = lw
#set        clobber             = no
#set        filewait    = yes
#set        cmbuflen = 512000
#set        min_lenuserarea     = 64000
set         imtype              = "fit"
set imextn="fxf:fit,fts,fits oif:imh"


# IMTOOL/XIMAGE stuff.  Set node to the name of your workstation to
# enable remote image display.  The trailing "!" is required.
#set        node                = "my_workstation!"

# CL parameters you mighth want to change.
#ehinit   = "nostandout eol noverify"
#epinit   = "standout showall"
showtype = yes

# Default USER package; extend or modify as you wish.  Note that this can
# be used to call FORTRAN programs from IRAF.

package user

task        $adb $bc $cal $cat $comm $cp $csh $date $dbx $df $diff    = "$foreign"
task        $du $find $finger $ftp $grep $lpq $lprm $ls $mail $make   = "$foreign"
task        $man $mon $mv $nm $od $ps $rcp $rlogin $rsh $ruptime      = "$foreign"
task        $rwho $sh $spell $sps $strings $su $telnet $tip $top      = "$foreign"
task        $touch $vi $emacs $w $wc $less $rusers $sync $pwd $gdb    = "$foreign"

task        $xc $mkpkg $generic $rtar $wtar $buglog                   = "$foreign"
```

```
#task       $fc = "$xc -h $* -limfort -lsys -lvops -los"
task        $fc = ("$" // envget("iraf") // "unix/hlib/fc.csh" //
               " -h $* -limfort -lsys -lvops -los")
task        $nbugs = ("$(setenv EDITOR 'buglog -e';" //
               "less -Cqm +G " // envget ("iraf") // "local/bugs.*)")
task        $cls = "$clear;ls"

if (access ("home$loginuser.cl"))
   cl < "home$loginuser.cl"
;

keep;   clpackage

prcache directory
cache   directory page type help

# Print the message of the day.
if (access (".hushiraf"))
   menus = no
else {
   clear; type hlib$motd
}

# Delete any old MTIO lock (magtape position) files.
if (deftask ("mtclean"))
   mtclean
else
   delete uparm$mt?.lok,uparm$*.wcs verify-

# List any packages you want loaded at login time, ONE PER LINE.
images          # general image operators
plot            # graphics tasks
dataio          # data conversions, import export
lists           # list processing

# The if(deftask...) is needed for V2.9 compatibility.
if (deftask ("proto"))
   proto        # prototype or ad hoc tasks

tv              # image display
utilities       # miscellaneous utilities
noao            # optical astronomy packages

keep
```

BADPIX MASK (Gay, 2003)

```
# untrimmed
5 334 1 4
51 53 127 133
52 53 134 253
52 53 253 483
52 53 1 2048
73 73 2017 2033
73 73 1 2048
78 78 367 453
78 78 1 2048
83 84 668 668
298 299 1081 2048
345 345 130 135
442 442 673 695
671 673 598 600
```

684 685 1247 2048
778 778 1867 1877
819 820 179 2048
834 835 1683 2048
1017 1019 1717 1721
1017 1018 1722 1727
1107 1107 1 2048
1116 1116 1 2048
1224 1225 1428 2048
1245 1245 482 494
1290 1291 1072 2048
1450 1451 28 2048
1417 1417 1745 1750
1554 1554 1889 1895
1582 1582 421 427
1684 1684 174 178
1686 1687 174 174
1758 1762 516 520
1803 1803 1 2048
1834 1834 778 781
1838 1842 134 139
1882 1883 1 840
1882 1882 838 2048
1897 1897 310 315
1901 1901 1 356
1907 1907 1740 1760

.MAG File

```
#K IRAF       = NOAO/IRAFV2.11EXPORT    version    %-23s
#K USER       = cpullen              name       %-23s
#K HOST       = unit7                computer   %-23s
#K DATE       = 2003-06-05           yyyy-mm-dd %-23s
#K TIME       = 04:35:25             hh:mm:ss   %-23s
#K PACKAGE    = apphot               name       %-23s
#K TASK       = phot                 name       %-23s
#
#K SCALE      = 1.                   units      %-23.7g
#K FWHMPSF    = 2.5                  scaleunit  %-23.7g
#K EMISSION   = yes                  switch     %-23b
#K DATAMIN    = INDEF                counts     %-23.7g
#K DATAMAX    = INDEF                counts     %-23.7g
#K EXPOSURE   = EXPTIME              keyword    %-23s
#K AIRMASS    = AIRMASS              keyword    %-23s
#K FILTER     = FILTERS              keyword    %-23s
#K OBSTIME    = UT                   keyword    %-23s
#
#K NOISE      = poisson              model      %-23s
#K SIGMA      = 0.                   counts     %-23.7g
#K GAIN       = ""                   keyword    %-23s
#K EPADU      = 1.                   e-/adu     %-23.7g
#K CCDREAD    = ""                   keyword    %-23s
#K READNOISE  = 0.                   e-         %-23.7g
#
#K CALGORITHM = centroid             algorithm  %-23s
#K CBOXWIDTH  = 5.                   scaleunit  %-23.7g
#K CTHRESHOLD = 1.                   sigma      %-23.7g
#K MINSNRATIO = 1.                   number     %-23.7g
#K CMAXITER   = 10                   number     %-23d
#K MAXSHIFT   = 5.                   scaleunit  %-23.7g
#K CLEAN      = no                   scaleunit  %-23b
#K RCLEAN     = 1.                   scaleunit  %-23.7g
```

```
#K RCLIP      = 2.                  scaleunit  %-23.7g
#K KCLEAN     = 3.                    sigma      %-23.7g
#
#K SALGORITHM = mode                  algorithm  %-23s
#K ANNULUS    = 22.                 scaleunit  %-23.7g
#K DANNULUS   = 5.                  scaleunit  %-23.7g
#K SKYVALUE   = 0.                  counts     %-23.7g
#K KHIST      = 3.                 sigma      %-23.7g
#K BINSIZE    = 0.1                sigma      %-23.7g
#K SMOOTH     = no                   switch     %-23b
#K SMAXITER   = 10                   number     %-23d
#K SLOCLIP    = 0.                 percent    %-23.7g
#K SHICLIP    = 0.                 percent    %-23.7g
#K SNREJECT   = 50                   number     %-23d
#K SLOREJECT  = 3.                   sigma      %-23.7g
#K SHIREJECT  = 3.                   sigma      %-23.7g
#K RGROW      = 0.                  scaleunit  %-23.7g
#
#K WEIGHTING  = constant             model      %-23s
#K APERTURES  = 12                   scaleunit  %-23s
#K ZMAG       = 25.                 zeropoint  %-23.7g
#
#N IMAGE              XINIT     YINIT     ID   COORDS              LID     \
#U imagename          pixels    pixels    ##   filename            ##      \
#F %-23s              %-10.3f   %-10.3f   %-5d %-23s               %-5d
#
#N XCENTER    YCENTER    XSHIFT  YSHIFT  XERR    YERR          CIER CERROR   \
#U pixels     pixels     pixels  pixels  pixels  pixels        ##   cerrors  \
#F %-14.3f    %-11.3f    %-8.3f  %-8.3f  %-8.3f  %-15.3f       %-5d %-9s
#
#N MSKY          STDEV         SSKEW         NSKY    NSREJ     SIER SERROR   \
#U counts        counts        counts        npix    npix      ##   serrors  \
#F %-18.7g       %-15.7g       %-15.7g       %-7d    %-9d      %-5d %-9s
#
#N ITIME         XAIRMASS      IFILTER             OTIME               \
#U timeunit      number        name                timeunit            \
#F %-18.7g       %-15.7g       %-23s               %-23s
#
#N RAPERT   SUM          AREA       FLUX         MAG    MERR    PIER PERROR   \
#U scale    counts       pixels     counts       mag    mag     ##   perrors  \
#F %-12.2f  %-14.7g      %-11.7g    %-14.7g      %-7.3f %-6.3f %-5d %-9s
#
107r1               965.000   995.000   1    107.pam.coo          0       \
  965.187    995.567    0.187   0.567   0.007   0.006         0    NoError   \
  111.2863       7.554567       2.194241       767    6       0    NoError   \
  30.          1.417         R                  6:06:48.53          \
   12.0164005.9      452.444    113655.1      16.054 0.004 0    NoError
```

.ans Transformation and Extinction Solution

```
cl> type std.pam.ans
# Thu 15:53:26 05-Jun-2003
begin   BFIT
       status  0       (Solution converged)
       variance        0.00274461
       stdeviation     0.05238903
       avsqerror       0.003515426
       averror         0.05929103
       avsqscatter     7.911924E-4
       avscatter       0.02812814
       chisqr          0.7807333
       msq             0.002611807
```

```
    rms             0.05110584
    reference       mB
    fitting         (BR+R)+b1+b2*XB+b3*BR
    weights         photometric
    parameters      3
        b1      (fit)
        b2      (fit)
        b3      (fit)
    derivatives     3
        0.1
        0.1
        0.1
    values  3
        4.248597
        0.278672
        -0.1007238
    errors  3
        0.06886289
        0.05204131
        0.01177141

# Thu 15:54:03 05-Jun-2003
begin   RFIT
    status  0       (Solution converged)
    variance        0.001376153
    stdeviation     0.03709653
    avsqerror       0.00143578
    averror         0.03789169
    avsqscatter     5.623257E-4
    avscatter       0.02371341
    chisqr          0.9584703
    msq             0.001309565
    rms             0.03618791
    reference       mR
    fitting         R+r1+r2*XR+r3*BR
    weights         photometric
    parameters      3
        r1      (fit)
        r2      (fit)
        r3      (fit)
    derivatives     3
        0.1
        0.1
        0.1
    values  3
        3.520395
        0.1009293
        0.008327574
    errors  3
        0.04797363
        0.03534715
        0.009378653

# Thu 15:58:35 05-Jun-2003
begin   IFIT
    status  0       (Solution converged)
    variance        0.01009456
    stdeviation     0.1004717
    avsqerror       0.01009277
    averror         0.1004628
    avsqscatter     0.009789092
    avscatter       0.09893984
    chisqr          1.000177
```

```
msq             0.009606113
rms             0.09801078
reference       mI
fitting         (R-RI)+i1+i2*XI+i3*RI
weights         photometric
parameters      3
        i1      (fit)
        i2      (fit)
        i3      (fit)
derivatives     3
        0.1
        0.1
        0.1
values  3
        3.535172
        0.04811165
        0.1618898
errors  3
        0.1958016
        0.1471552
        0.105398
```