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3-D Study of the Glowing Eye Nebula, NGC 6751

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Abstract. In these proceedings we present a detailed, multiwavelength spectral and image analysis of the complex planetary nebula, NGC 6751. This PN consists of multiply shells and a bipolar outflow. Using the Manchester Echelle Spectrometer (MES) at San Pedro Mártir Observatory in Baja California, we acquired optical, high spectral resolution, longslit observations across this nebula, with particular focus on the highly structured inner region near the bipolar outflows. We used the interactive morpho-kinematic reconstruction software Shape to derive the 3-D morpho-kinematic model of the nebula that closely resembles the observed profiles and image of NGC 6751. The inner region consists of a filamentary bubble surrounded by a clumpy ring. The ring is tilted with-respect-to the line-of-sight and is encircled by a disk-like structure. Emanating from the central regions are two, point-symmetric outflows which flow into two lobes seen in a ground based, Gemini image. Farther out are a faint inner halo and a fragmented outer halo. This nebula lies in the galactic plane and appears to be moving through a gas-rich environment. Deep, ground-based images indicate a veil-like structure to the NE, which is most likely nearby ISM. Our spectra indicate a large velocity difference between this gas and NGC 6751, confirming that this structure is indeed ISM material.

1. Introduction

NGC 6751 is an impressive and intricate planetary nebula (PN), that has been given the name the "Glowing Eye Nebula" due to the appearance of the central bubble as seen in high resolution images. This PN has been observed across a wide range in wavelengths from the mid-infrared (*Spitzer*) to the optical (*HST*) and at various levels of spatial resolution. This makes NGC 6751 an ideal target for studying the kinematics of a PN and it's environment. The Manchester Echelle Spectrometer at San Pedro Mártir (MES-SPM) is a perfect instrument for this work. Using narrow-band, MES-SPM images we compared these with images taken by *HST*, Gemini and *Spitzer* to get a first pass on the form of this PN. Combining this with the high-resolution spectral capability of this instrument, we made the most detailed study to date of the kinematics and structure of NGC 6751. We also sought to confirm that the emission to the NE of the PN is not associated with the nebula as suggested by Chu et al. (1991).

2. Observations

This study is primarily based on high resolution, long slit spectra acquired with MES-SPM at San Pedro Mátir Observatory in Baja California, Mexico. MES-SPM was installed on the 2.1 m telescope using the f/7.5 secondary. We acquired all spectra using a SITE detector consisting of 1024×1024 pixels, binned 2×2 and observed through a Hα+[N II] filter. We chose 9 slit positions across the field. Slit a passes through the center of the nebula with a position angle (PA) equal to 0°. Previous, spectral observations of this PN indicated an outflow along a line at a positional angle (PA) of $\sim$ 100° (Gieseking & Solf 1986). Thus, we chose to position slits b–i parallel to an axis at this PA in order to study the extent of this outflow region. Slit b, to the N, passes through the extended emission and slits c and i pass through the inner halo. All spectra were wavelength calibrated using observations of a ThAr lamp.

Supplemental data included deep Hα+[N II] and [O III] images taken with MES-SPM (Figure 1). We also included a Gemini, GMOS image taken in three filters, Hα, [S II] and [O III], for a total observing time of one hour (http://www.gemini.edu/node/11329). This image was provided to us by Christopher Onken from the Australian Gemini Office (Gemini Program II GS-2009A-Q-22, PI Terry Bridges). This image won the 2009 Gemini School Astronomy Contest and was submitted by high school student Daniel Tran. Image credits are Daniel Tran (PAL College), Travis Rector (U. Alaska Anchorage), Terry Bridges (Queen's U.) and the Australian Gemini Office. In addition, we made use of an 8μm, *Spitzer* image taken from the archives [1], an image from the Hα composite full sky map (Finkbeiner 2003) and an optical, *HST* image taken from the gallery of the Hubble Heritage Project [2].

3. Morphology and Kinematics

Deep, narrow band images show NGC 6751 to have a detailed, complex structure. A thick, knotty ring surrounding an inner, filamentary bubble is especially evident in the *HST* and Gemini images. The MES-SPM, [O III] image brings out the inner halo and the bipolar outflow is quite obvious in the MES-SPM, Hα+[N II] image (see Figure 1). The Gemini image further reveals that the outflows are extending into two lobes of material. The MES-SPM images and Gemini image show a filamentary outer halo beyond the central regions of the nebula.

We found that the PN is best described by five components. These include a central bubble, tilted ring ($\sim$ 10°), disk, bipolar outflow and inner halo. Using slits a and g, which pass through the central star, we measured a systemic velocity of V_{sys} = -31.7(±2) km s^{-1}. The central bubble is expanding at $V_{exp} = \sim 42$ km s^{-1} (where V_{exp} = V_{hel} - V_{sysl}), which is relatively high for this type of structure (Richer et al. 2010). Images, such as the *HST* or Gemini images, suggest that there is filamentary material central to the bubble. However, an inspection of our spectra indicate that the filaments are on the surface of the bubble and could be dense material here. Just outside of the central bubble is a ring of material. Our spectra indicate the ring is expanding at $V_{exp} \approx 40$ km s^{-1} in the east and $V_{exp} \approx 7$ km s^{-1} in the west. The ring itself is

[1]The *Spitzer Space Telescope* is operated by the Jet Propulsion Laboratory, California Institute of Tech

[2]*HST* image credit: NASA, ESA, and the Hubble Heritage Team (STScI/Aura)

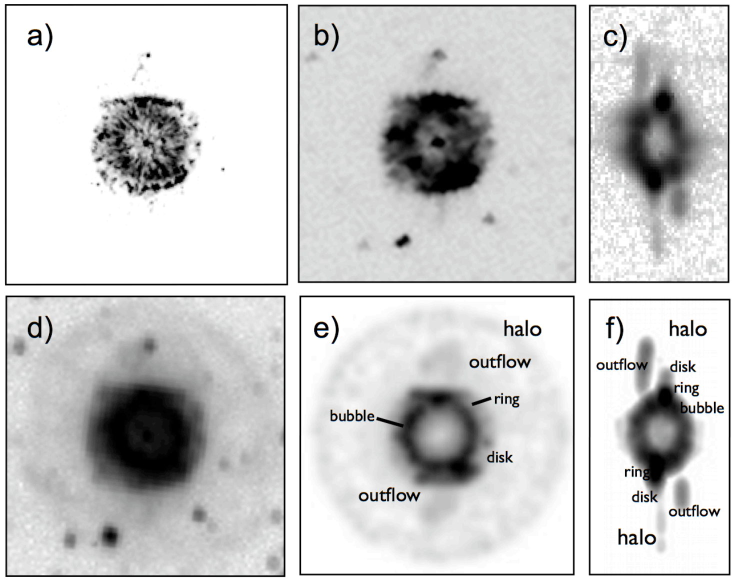

Figure 1. Here we compare various observational views of NGC 6751 with our Shape model. a) *HST* image, b) SPM, Hα+[N II] image, c) [N II] spectra for slit g, d) SPM [O III] image, e) Shape model, f) model PV diagram.

surrounded by a disk of knotty material. This could be gas in the ring that has been swept back and is being photo evaporated by the emission from the central star. The bipolar outflow is expanding at V_{exp} ~79 km s^{-1}. The outer halo is expanding rapidly with V_{exp} = 16 km s^{-1}, while the inner halo is expanding more slowly, with V_{exp} = 2 km s^{-1}.

We made a 3-dimensional, morpho-kinematic reconstruction of NGC 6751 using the program Shape (Steffen & López 2006). With this program, various forms can be filled with particles and each particle system can be given a separate velocity law to describe how the nebula is expanding. An artificial slit can then be placed on the 3-D representation of the nebula to make artificial spectra. These spectra can be compared with real, high-resolution spectra to search for the best structural description of a PN. A similar procedure was followed by García-Díaz et al. (2009) to model the PN, NGC 6337.

To make our reconstruction of NGC 6751, we used slits a and c–i. In this work, we applied a Hubble flow type velocity law to the particle systems used. This velocity law can be described as $v = k \cdot r/r_0$, where k is a constant, r is the distance from the source and r_0 is the radius at which the velocity k is reached. The central bubble was modelled using a filled sphere and we modeled the inner halo using a thin shell. Tori were used to model the ring and disk surrounding the ring. We found the ring is tilted out of the plane of the sky in the east by $\sim 10°$ and also appears to be slightly warped about the N-S axis. Segments of spheres described the bipolar outflows. Interestingly, we found that the outflow is inclined by $23° \pm 5°$ with-respect-to the plane of the sky, which is not perpendicular to the ring as one might expect.

Aside from our Shape reconstruction, we also explored the nature of the extended emission to the NE. A *Spitzer* 8μm image shows that this emission continues farther to the N. It is also quite evident that NGC 6751 is in a gas rich environment as seen in Hα images from the full sky survey in Hα (Finkbeiner 2003). Our spectra that pass through this region to the NE indicate the emission has a range in heliocentric velocity from 26–34 km s^{-1}. Considering the heliocentric, systemic velocity of this PN is -41($\pm$ 2 km s^{-1}), the velocity of the extended emission is quite different, indicating it is not related to the nebula. This confirmed the observations by Chu et al. (1991), which also showed no relation between this emission and the PN.

4. Conclusions

In this work we investigated the 3-dimensional structure and kinematics of the PN, NGC 6751 using high resolution, [N II] spectra taken with MES-SPM. Using the software Shape, we searched for the best structural description of the nebula. We found that this PN consists of a central bubble expanding at ~42 km s^{-1}, a warped ring tilted by 10° out of the plane of the sky, and a clumpy disk just outside of the ring. Two bipolar outflows extend to the east and west side of the nebula, with an expansion velocity of ~79 km s^{-1} and inclined by ~23° to the plane of the sky. These outflows can be seen in Gemini and *HST* images of the PN. Outside of the central region is an inner halo expanding at ~15 km s^{-1} and farther out is a clumpy, outer halo. The inner halo is quite evident in MES-SPM [O III] images.

To the NE of the PN there appears extended emission. We compared the velocity of this emission with the systemic velocity of NGC 6751 and found they differ by ~70 km s^{-1}. This confirmed the observations by Chu et al. (1991) that this emission is not associated with the nebula. *Spitzer* 8 μm and Hα images (Finkbeiner 2003) of the surrounding field of NGC 6751 indicate this nebula is in a gas rich environment.

Details of this work will appear in the October issue of the Astrophysical Journal (Clark et al. 2010).

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