Planetary Nebulae: An Eye to the Future
Proceedings IAU Symposium No. 283, 2011
A. Manchado, L. Stanghellini & D. Schönberner, eds.

doi:10.1017/S1743921312011362

3D ionization structure and kinematics of NGC 2392

Reginald J. Dufour[1], Jonathan N. Sick[1,2], Patrick M. Hartigan[1], Richard B. C. Henry[3], Karen B. Kwitter[4] and Joaquin Bohigas[4]

[1]Rice University, email(RJD): rjd@rice.edu

[2]currently at Kingston University [3]University of Oklahoma [4]Williams College [5]OAN/UNAM

Abstract. We discuss the 3D morphology, ionization structure, and kinematics of NGC 2392, the "Eskimo," based on new and archival HST imagery and new long-slit echelle spectroscopy. High spatial resolution ionization maps of the nebula were made from HST WFPC2 imagery and compared with their velocity structure in various emission lines from echelle spectra taken with the 4m telescope at Kitt Peak. The imagery and spectra were then compared to map the kinematics of the nebula in several emission lines and decode the 3-dimensional morphology and ionization structure of the nebula, including that of C^{+2} from C III] 1909Å for the first time.

Keywords. planetary nebulae: individual (NGC 2392)

1. Introduction

During the past three decades there have been numerous studies of the morphology and kinematics of NGC 2392 –the "Eskimo;" most recently by Phillips & Cuesta (1999) and O'Dell *et al.* (2002). While these studies have been in general agreement regarding its kinematics and morphology, additional information is afforded from new HST WFPC2 imagery, modern deep longslit echelle spectroscopy, and photoionization modeling of different structures. Here we present new HST WFPC2 imagery, echelle spectra, photoionization models of three components, and combine them to develop an improved 3D spatio-kinematical model for the nebula.

HST WFPC2 Imagery We processed over 50 HST WFPC2 images of NGC 2392 in eight bandpasses: F185W (which includes the C III] 1909Å lines), F469N (He II 4686Å), F487N (Hβ), F502N ([O III] 5007Å), F547M (continuum), F656N (Hα), F658N ([N II] 6583Å, and F673N ([S II] 6723Å). LACosmic (van Dokkum 2001) was used to remove cosmic rays and the individual combined images were aligned using IRAF routines. The processed F547M images were scaled and subtracted from the emission line images and calibrated using IUE and optical spectrophotometry of five 2″ circular aperture locations from Barker (1991). Line ratio maps of the nebula at 0.1″ resolution were produced to study the ionization structure and the line-of-sight extinction across the nebula. This extends the earlier results presented by O'Dell *et al.* with more line ratio maps. Space does not allow presentation of our six ionization maps here but they can be downloaded from the web at http://www.ruf.rice.edu/∼rjd/e skimop.pdf. The two most notable (and unexpected) new results from our expanded imagery study are (a) the azimuthally averaged reddening mapped by the c(Hβ) parameter increases outward from a minimum of ∼ 0.10 in the center of the nebula to ∼0.5 at a 22″ distance from the central star and (b) the C III]/[O III] 1907+9Å/5007Å ratio shows a significant decrease in the cores of the strong [O III] inner filaments of the nebula surrounding the central star. We interpret the radial reddening increase (a) as due to the effects of internal dust increasing outward in the nebular shell and the drop in C III] relative to [O III] (b) as primarily due to

collisional quenching of the C III] 1907Å line which has a critical density of 5×10^5 cm^{-3} compared to 7×10^6 cm^{-3} for [O III] 5007Å.

Photoionization Modeling We used a 3D line-of-sight integration algorithm (Henry *et al.* 1999) with the CLOUDY photoionization code (Ferland *et al.* 1998) to model the ionization and emission-line surface brightness variations seen on our imagery. We were successful in developing models matching three distinct morphological components of NGC 2392: (a) the highly ionized outer shell, (b) the inner filamentary network, and (c) the low ionization fliers located between the boundaries of the inner and outer shells. For all the modeling we settled on a central star blackbody SED with $T_{\rm eff}$=74,000 K, $\log(L/L_\odot = 4.0)$, and concentrated on density variations and geometrical considerations in matching the emission-line variations. The models most successful in fitting the emission-line variations seen indicated that (a) was a thin shell, (b) the densities of the inner filaments were ∼300 cm^{-3} at the edges rising to higher than 3000 cm^{-3} in the centers (and possibly as high as $\sim 10^5$ cm^{-3} from the C III] decrease), and (c) the fliers had high density heads where [S II] was collisionally quenced but appears strong in the tails due to lower densities and that there is no clear evidence that they are N-rich.

Kinematics from KPNO 4m Echelle Spectroscopy Echelle spectra of five positions across the nebula (slit on the central star and stepped ±3.5″ & 6.0″ E-W) were obtained with the KPNO 4m Mayall telescope with a 1.0″ wide 50″ long slit at a PA of 13°. The range of emission lines studied was from Hβ to the [S II] 6717,31Å line and the velocity resolution was ≈7 km/s. These data enabled the kinematics of many of the morphological structures evident on the HST WFPC2 emission-line images to be determined and the development of a 3D spatio-kinematical model of NGC 2392 in more detail than in previous studies. We developed maps of the velocity structure of NGC 2392 in each of the emission lines for which we had HST imagery and also produced colorized *ratio* maps of the kinematics of sets of emission lines from different ions for the five slit positions.

Summary: our 3D model Taken together, these high spatial resolution images and high velocity resolution spectral data in several prominent spectral lines combined with the LOS integrated photoionization modeling enabled an improved understanding of the structure of NGC 2392 compared to previous investigations. We presented a "cartoon" drawing of the 3D structure of the nebula which compares well (overall) with the models in recent investigations, but differs in details such as the inner [O III] strong filaments being in a nearly spherical distribution around the central star, but the strong [N II] inner knots and filaments are more distant structures seen in projection forming a "tubular" shaped system (e.g., like NGC 7009 seen face-on) with the major axis tilted ∼20° in the LOS with the S part being towards us. Moreover, the diffuse low ionization "skirt" below and above the central structure is in the LOS and kinematically an extension of the tubular inner system while the so-ca lled "fliers" appear to be low ionization cometary features (similar to those seen in NGC 7293) moving (apparently slowly) nearly in the plane of the sky (check out the URL for illustrations).

Acknowledgments RJD, JNS, RCBH, & KBK acknowledge support by AURA/STScI Cycle 13 program GO10822 and NSF; PMH by NASA and DOE; and JB by Conacyt OAN/UNAM.

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