PLANETARY NEBULAE: THEIR EVOLUTION AND ROLE IN THE UNIVERSE
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Keck HIRES Spectra of the Planetary Nebula NGC 7009

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Abstract. With strategically important diagnostic lines of, e.g., [O II], [O III] and [S II], secured with the Keck I HIRES, we obtained electron densities and temperatures, while retaining 3-D spatial information for the well-known elliptical nebula NGC 7009: we found that the temperature fluctuations exceeded those reported in the HST imaging study, i.e. $T_e \sim 9500 - 11500$ K; we also found large velocity dispersions in the [S II] maps (with extremely high density fluctuations, i.e. $\log N_e = 3.8 - 4.5$), but not in the [O II] ones. The [S II] map indicates that this emission is from numerous small-scale blobs of size $\sim 1''$ spread over a wider region, while [O II] shows no such evidence. The [S II] emission is likely to be due to shock excitation, while the [O II] emission is perhaps due to photoionization.

1. Observation and Data Reduction

The long-slit capability of the Keck I HIRES enabled us to obtain high S/N, high-dispersion (~ 0.1Å), and high spatial resolution ($\sim 0.8''$) spectral line profiles. In 1998 August 13–15, we obtained HIRES spectra, with the slit placed along the major and minor axes of the bright nebular region. For our observations, we chose the following four HIRES settings: 1) $14'' \times 0.862''$ (8530–6309Å; red collimator), 2) $10'' \times 0.862''$ (5130–7475Å; red collimator), 3) $7'' \times 0.862''$ (3100–4100Å; red collimator) and 4) $3.5'' \times 0.862''$ (3450–5900Å; blue collimator).

Fig. 1 shows successive steps in the data reduction procedure for the minor axis spectral data (placed along the North-West rim), as well as the resulting density contour map derived from the [S II] 6710/6730 line ratios. While reducing the spectra, spatial information is retained along both the minor (PA$=-13°$) and major axes. The blue-shifted image regions yield information on the physical conditions in the foreground ionized gas, while the red-shifted regions correspond to receding gas in the rear.

2. Emission Lines and Physical Conditions

We obtained diagnostic maps from the [O II], [O III], [S II] and [Ar IV] Keck HIRES images. The [O III] images yield the temperature contour map (T_e), while the other three lines give the density (N_e). We found large temperature

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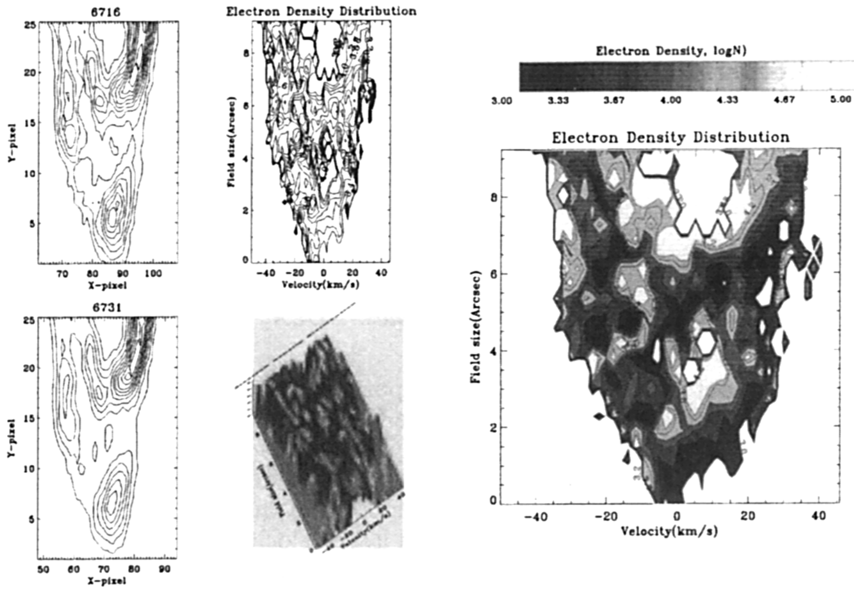

Figure 1. The electron density distribution along the minor axis of NGC 7009: a) the left 4 panels show the data reduction process, using the [S II] 6710 & 6730 line ratio (the CCD pixel scale is shown), and b) the right panel shows the electron density contour map; the radial velocity component is plotted along the horizontal axis, while the vertical axis gives the sky position along the minor axis of the NGC 7009 image.

fluctuations in the [O III] lines, which is perhaps caused by emission from two different regions: (1) fast moving (20–40km s^{-1}), relatively cold gas at $T_e \sim$9500 K, and (2) slowly expanding (20 km s^{-1}), relatively hot gas at $T_e \sim$11000–12000 K. Hence, the foreground region is likely to be cold, while the the background region is relatively hot.

The electron densities derived from the [O II] 3726/3729 line ratio map are in the range log $N_e = 4.0 - 4.3$, and the [O II] emission lies within a narrow zone in the slowly expanding region (2). The [Ar IV] images give a similar result. However, we found huge density fluctuations, log $N_e = 3.8 - 4.5$, in the [S II] 6710/6730 maps (see Fig. 1). These fluctuations also have velocity dispersions at least twice as large as expected from the other lines. The [O III], [Ar IV], and especially the [O II] maps, together indicate that the [S II] emission is of shock excitation origin, i.e. the slowly expanding gas in region (2) has been "bulldozed" by a fast wind moving at $\sim$ 40 km s^{-1}.

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