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HIGH DISPERSION SPECTROSCOPY OF THE YOUNG PLANETARY NEBULA M2–9[1]

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RESUMEN

Hemos obtenido espectroscopía echelle de rendija larga en el intervalo 3600 – 6800 Å de esta nebulosa bipolar y a partir de los perfiles de las líneas de emisión en la región central encontramos evidencia de eventos asimétricos de pérdida de masa.

ABSTRACT

We have carried out 3600 – 6800 Å long slit echelle spectroscopy of this bipolar nebula and from the profiles of the emission lines close to the nucleus we find evidence of asymmetric mass loss events.

Key words: **PLANETARY NEBULAE: INDIVIDUAL (M2–9)**

1. INTRODUCTION

M2–9 is a bright nebula that has been studied extensively (e.g., Allen & Swings 1972; Calvet & Cohen 1978; Schwarz et al. 1997). The nebula has bipolar morphology, seen almost face-on of approximately $12'' \times 48''$ with extensions that reach up to $60''$ from the nucleus. It has condensations symmetric relative to the equatorial plane that show motions parallel to it and reflection 'ansae' in the external parts at high velocities (Schwarz et al. 1997).

It is a very dust rich nebula; it shows very high reddening in the center, $A_V \sim 5.35$, significantly different to that in the lobes, $A_V \sim 2.70$, (Calvet & Cohen 1978); also a significant fraction of the light from the lobes can be attributed to dust dispersion

The visible star has been assigned a spectral type B (Calvet & Cohen 1978), and a hot, compact component has been proposed as the exciting source. According to Schwarz et al. (1997) the double system can then account for the ionization of the O^{++} gas from the hot component, while the low temperature component would be the central source in the visible region and the possible interaction of the binary system would produce the extreme collimation of the nebula. An accretion disk around the compact star would explain the fast wind collimation. Schwarz et al. (1997) estimate a distance of 650 pc for the object. At this distance the bolometric luminosity is 550 $L_\odot$ and its dynamic age is 1200 years. This luminosity corresponds to an AGB star.

2. OBSERVATIONS

Long slit spectra were obtained with the REOSC echelle spectrograph at the 2.1-m telescope of the Observatorio Astronómico Nacional in San Pedro Mártir, Baja California in April 1996 with a 1024 × 1024 Tektronix TK1024AB CCD with Metachrome II coating. The spatial resolution of the system is $0.88''$/pix and the spectral resolution corresponding is of 0.13 Å/pix at 3700 Å and of 0.24 Å/pix at 6560 Å. The slit was oriented with a position angle 175° to contain the central star and the lobes along the slit. The isocontours of high emission lines are shown in Figure 1.

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[1]Based on observations carried out at Observatorio Astronómico Nacional in San Pedro Mártir, Baja California, México.

3. LOBES

The emission spectrum of the lobes is dominated by the Balmer lines; it also shows He I, [N I], [N II], [O I], [O II], [O III], [Ne III], [S II] and [S III]. The intensity isocontours for the bright emission lines are displayed in Figure 1. Our observations confirm previous results (e.g., Balick 1989; Goodrich 1991), namely, the emission lines show a negative velocity for the southern lobe and a positive velocity for the northern lobe, relative to the mean velocity. The typical difference between the bright knots (separated $\sim 30''$) is 30 km s^{-1}.

There are intensity maxima that correspond to individual condensations; they show peculiar velocities relative to the mean nebular velocity. These condensations have been identified previously by Kohoutek & Surdej (1980). We can identify S3 and N3 in [O III] and N1, N2, and N3 in [N II]. In addition there is a low ionization condensation present in [N II] and in [O II] located $3''$ South of the center with a velocity of ~ -20 km s^{-1} relative to the systemic velocity that had not been observed before. We compare our observations with those of Balick (1989) and we can ascertain that it was not present at the time of their observations, December 1986. A condensation with a velocity of 30 km s^{-1} would require 9 yrs to reach a $3''$ separation at a distance of 650 pc. This change is consistent with the short timescale variations in the lobe structure reported previously (Allen & Swings; Kohoutek & Surdej 1980).

The differential reddening of the central and of the lobes (determined by Calvet & Cohen) can be appreciated from the comparison of the relative intensity profiles of Hα/Hβ. From this ratio and assuming a normal extinction law we derive $A_V = 2.17$ C(Hβ) $= 2.4 \pm 0.2$ in the lobes; where C(Hβ) is the logarithmic reddening correction at Hβ.

4. NUCLEUS

The continuum is weak, with no appreciable absorption lines; it is not possible from it to determine the stellar spectral type. The emission spectral features are a complex system, not only the usual set of features corresponding to a high excitation PN are present, but also there are relatively strong Si II, [Fe I], [Fe II], [Fe III], [Fe IV] and [Ni II] lines. The Si II, [Fe II] and [Fe III] lines are also observed in η Car (Thackeray 1967) and in the slow nova RR Tel (Thackeray 1977). For the nucleus we derive $A_V = 6.9 \pm 0.2$

All the nuclear emission lines are wide, with a FWHM of at least 50 km s^{-1}, some lines have widths as large as FWHM $\sim$ 100 km s^{-1}. Several emission lines show double maxima in the nucleus, (H I, [O III] 5007 and 4959, [Ne III]), while others show a single maximum (He I, [N II] 6584 and [O I] 6300). A list of some of the characteristics of the strongest lines are given in Table 1, where we include intensity, radial velocity and width. From these characteristics we try to construct a model of the emitting region.

The emitting regions in the core are of relatively high density as has been pointed out by other authors (e.g., Allen & Swings 1972). The different relative intensities permitted vs. forbidden in the maxima of the emission lines are an indication of different physical conditions. We also present in Table 1 the critical densities for the forbidden lines. The receding emission is produced in a high density medium ($N_e > 10^6$ cm^{-3}), while the approaching component is produced in a lower density medium ($N_e < N_{critical}$).

The distribution of the material of the central regions is difficult to interpret. The two emission peaks in Hα have been interpreted by Balick as a single emission with overlying self-absorption; however, the two maxima in [O III] do not support this interpretation, rather we consider that there are 3 distinct emitting regions: (a) an intermediate density region at -35 km s^{-1} relative to the mean, (b) a high density receding one at $+35$ km s^{-1}, and (c) a third one with the same velocity within $\pm$ 5 km s^{-1} as the system velocity (the Balmer line contribution at this velocity is hidden by the two brighter maxima). These velocities are measured relative to the mean of the lobes which corresponds to a heliocentric velocity of 60.7 km s^{-1}. It should be noted that both Balmer components show the same reddening, indicating that they are both at the essentially the same location.

There are systematic differences in the velocity profiles from the high ionization species to the low ionization ones. Following the He I, [O III] and [O II] lines they correspond to increasing spread in velocities, that can be associated with larger distances from the central source. The profiles in [O I] lines do not follow this pattern.

These double maxima profiles are usually attributed to a rotating circumstellar disk, however we rule out this possibility. The rotation period of a disk surrounding a star is $P(yrs) = 0.6(M/M\odot)/(v/35 \text{ km s}^{-1})$; the timescale of variation is of a few months and would have been readily observable. Comparing our spectra with that of Balick (a 10.3 yr interval) we find no evidence of any change in the core profile, furthermore we have more recent spectra (May 1997) that do not show any significant change. Alternatively, we propose that the

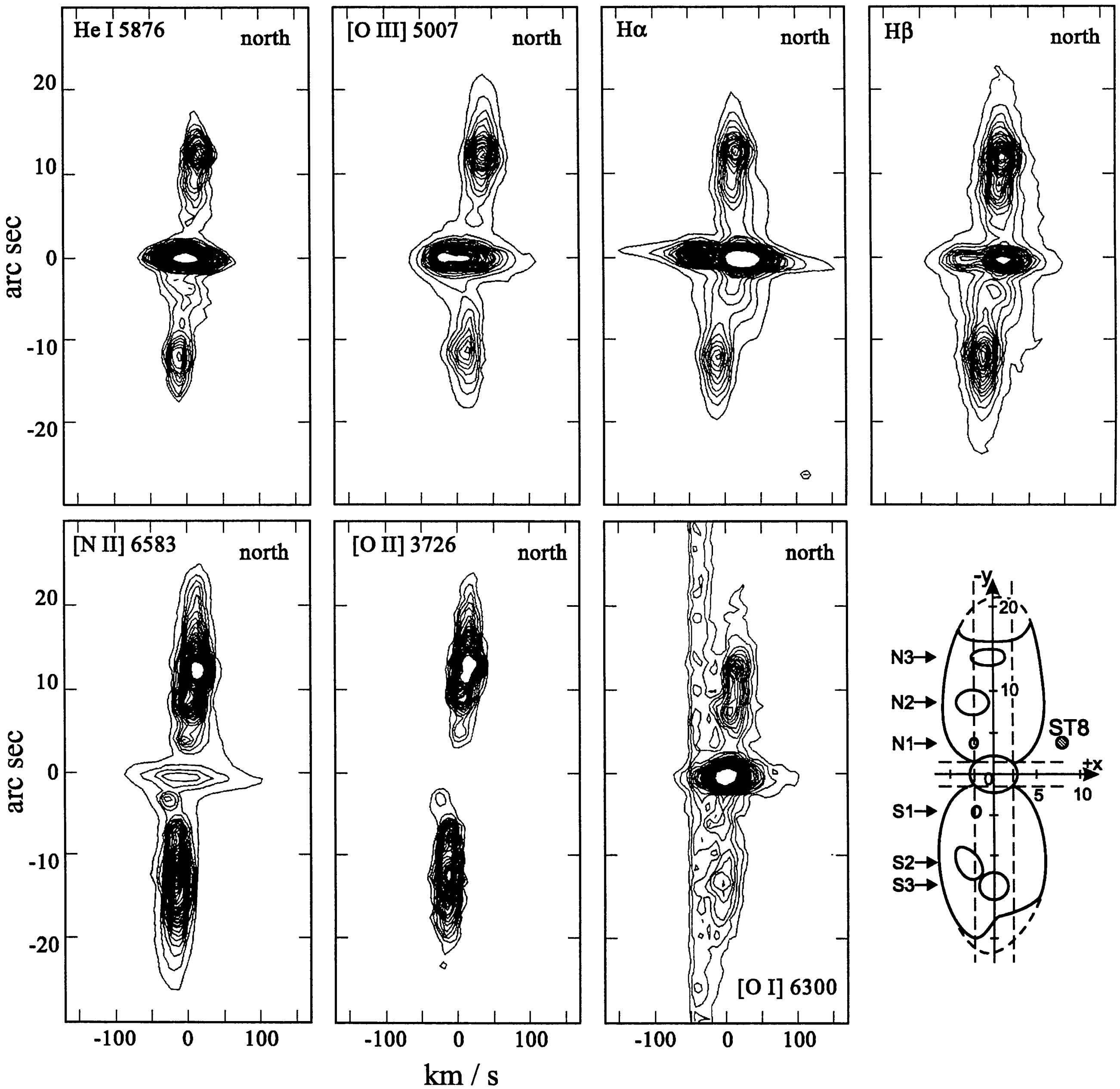

Fig. 1. Isocontours of bright emission lines (Hα, Hβ, [O III], He I, [O II], and [N II]). The contours show moderate velocity in the lobes and high velocities in the nucleus. In Hα and Hβ the significant larger reddening at the nucleus can be noticed. In Hα, Hβ, and [O III] the central emissions have two maxima. The peak in Hα is *redshifted*, while that in [O III] is *blueshifted* from the mean velocity of the object. The He I emission is wide and shows a single peak in the nucleus at the systemic velocity of M2–9. A bright low ionization knot displaced (~ -20 km s^{-1}) 3″ South from the nucleus is observed in [O II] and [N II]. Also included is a diagram of the nebula and condensations from Kohoutek & Surdej (1980) with the slit indicated.

central star is continuously ejecting material, in accordance with the small condensation 3″ south of the center that was not present 10 years ago.

The mass involved in the emission region (assumed to be optically thin) is

TABLE 1

KINEMATICS OF THE NUCLEUS

λ_0	ion	V_{hel}	flux (10^{-15}) erg cm^{-2} s^{-1}	FWHM km s^{-1}	critical density cm^{-3}
6563	Hα	26.6	826.	41 ± 2	...
		96.5	2950.	51 ± 2	...
4861.	Hβ	6.5	127.7	40 ± 2	...
		70.0	102.	51 ± 2	...
4340.	Hγ	5.7	12.9	38 ± 3	...
		65.8	41.6	59 ± 3	...
5876.	He I	54.0	79.3	65 ± 3	...
6678.	He I	51.1	41.1	57 ± 5	...
6583.	[N II]	63.9	65.1	92 ± 5	8.6×10^4
6300.	[O I]	63.2	50.9	47 ± 5	1.9×10^6
6363.	[O I]	59.3	20.6	42 ± 5	1.9×10^6
3726.	[O II]	18.6	6.8	45 ± 8	4.5×10^3
		88.8	1.50	36 ± 8	...
3729.	[O II]	19.4	3.8	90 ± 8	3.3×10^3
5007.	[O III]	19.4	220.	56 ± 2	7×10^5
		60.7	151.	70 ± 2	...
4959.	[O III]	7.9	61.3	46 ± 2	7×10^5
		43.6	45.3	53 ± 2	...

$$M_{ion} = \frac{4\pi d^2 m_H \epsilon^{1/2} I(H\alpha)}{4\pi j_{H\alpha} N_{FL}} \quad ,$$

where $I(H\alpha)$ is the Hα flux corrected for reddening, $4\pi j_{H\alpha}$ is the volume emissivity at the temperature T_e and ϵ is the filling factor. Substituting the appropriate values this expression becomes

$$M_{ion}(M_\odot) = \frac{1.71 \times 10^{-5} \epsilon^{1/2} (d/650)^2 [10^{0.68 C(H\beta)} \times F(H\alpha)_{-12}]}{N_4 f(T_4)_{H\alpha}} \quad ,$$

where N_4 is the electron density from forbidden lines in units of 10^4 cm^{-3}, d is the distance in pc, T_4 is the electron temperature in 10^4 K, $F(H\alpha)_{-12}$ is the observed flux in 10^{-12} erg cm^{-3} s^{-1}, C(Hβ) is the logarithmic reddening correction at Hβ, $f(T_4)_{H\alpha}$ is the temperature correction for the Hα emissivity (assumed unity for $T_4 = 1$), and ϵ is the filling factor.

Thus for $\epsilon = 0.1$, C(Hβ) = 3.17, $T_4 = 1$, and a density of 10^5 cm^{-3} the approaching component corresponds to 6×10^{-5} $M\odot$; for a density of 10^7 cm^{-3} the receding component corresponds to 2.2×10^{-6} $M\odot$.

In addition, Hα shows very wide symmetric wings that we can follow in our spectra up to ± 4500 km s^{-1}. Balick (1989) reports the wide component of Hα to be 11000 km s^{-1} at its base. Our observations show the same profiles as shown by Balick in his Figure 3. Extended wings in Hα have also been found in the dusty bipolar PNe Mz-3 (López & Meaburn 1983), in M1-91 (Goodrich 1991), and in IC 4997 (Miranda, Torrelles, & Eiroa 1996), and in symbiotic stars like HM Sge (Wallerstein 1978). Following the treatment of López & Meaburn we find that in the case of a stellar wind it would require a mass loss rate higher than 5×10^{-4} $M\odot$, which is not consistent with the expected value of 10^{-7} to 10^{-9} $M\odot$ for a PN in its fast mass loss phase (Schoenberner 1983); moreover the expected profile for a spherical wind would be of elliptical shape. We find that we can adjust the extended wind profile to a symmetric structure centered about V_{hel} = 54 km s^{-1} that can be fit to a lorentzian profile for 450 to 4500 km s^{-1} from the center. López & Meaburn attribute this extended feature to scattering in the nucleus.

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