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He 2-104: A LINK BETWEEN SYMBIOTIC STARS AND PLANETARY NEBULAE?*

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ABSTRACT

We present ultraviolet, optical, and infrared observations of He 2-104 and make estimates for some of the physical properties of the nebular shell. We argue that He 2-104 is in transition between the D-type symbiotic star and bipolar planetary nebula phases and, as such, represents a link between subclasses of these two types of objects. Our model includes a binary system with a Mira variable and a hot, evolved star. Previous mass loss has resulted in the formation of a disk of gas and dust around the whole system, while the hot star has an accretion disk which produces the observed highly ionized emission-line spectrum. Emission lines from cooler, lower-density gas is also observed to come from the nebula. In addition, matter is flowing out of the system in a direction perpendicular to the disk with a high velocity and is impacting on the previously ejected red-giant wind and/or the ambient interstellar medium.

Key words: nebulae: planetary–stars: symbiotic–mass loss

1. Introduction

Astronomers who are not specialists in research on symbiotic stars and planetary nebulae tend to think of them as two groups of fairly homogeneous entities. It is true that in each case there is one model which explains in a general way many of the phenomena observed in these objects. Symbiotic stars are thought to be binary systems in which interactions between a very cool star and either a hot star or a main-sequence star result in the production of an emission-line spectrum. Many of the observed characteristics of planetary nebulae can be explained by postulating an evolved star ejecting the outer portions of its atmosphere as it makes the transition between the red-giant and the white-dwarf phases of evolution.

However, as with most classes of astronomical objects, there are subgroups that have markedly different characteristics. For symbiotic stars a division can be made based on photometry in the near-infrared. Symbiotic stars with infrared spectra that reveal the presence of warm dust are called D-type; those which at infrared wavelengths look like cool stars are called S-type. Many of the D-type symbiotics have turned out to have Mira variables as the cool component (Whitelock 1987), and a few have been shown to have bipolar nebulae (Viotti 1987; Taylor 1988). Another major difference from one symbiotic star to another is the level of ionization of the spectral lines. Some show highly ionized species such as [Fe VII], while others

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have emission lines from only moderately ionized atomic species.

With planetary nebulae a number of subdivisions can be made depending on the characteristics that are of interest. For example, there are low-temperature central stars ($T < 30{,}000$ K) and ones with exceedingly high temperatures ($T > 200{,}000$ K). As a consequence, ionization levels differ greatly among planetary nebulae. These differences can be viewed as the result of stars with a modest range of stellar masses following evolutionary tracks to the white-dwarf state. A complex problem is the striking differences among nebular morphologies. Classification schemes and mechanisms for producing the various observed morphologies have been proposed recently by Zuckerman and Aller (1986) and by Balick (1987). Possible means for producing different nebular morphologies include the mutual interactions of stars in binary systems (Livio, Salzman, and Shaviv 1979; Pilyugin 1987), interacting winds (Kwok 1975; Balick 1987; Soker and Livio 1988; Icke, Preston, and Balick 1989), magnetic fields (Pascoli 1987), and combinations of the aforementioned (Morris 1987).

The reason for beginning this paper with some general remarks about symbiotic stars and planetary nebulae is that some investigators have proposed that there might be an evolutionary link between them (Lutz 1988; Schwarz 1988; Gutiérrez-Moreno 1988). Although other classes of objects, in particular the OH-IR stars, appear to be closely connected with the eventual production of many planetary nebulae, it is the thesis of this paper that a link between D-type symbiotic stars and at least some of the bipolar planetary nebulae should be considered. This hypothesis has emerged from studies of a small number of objects that have considerable overlap in the characteristics that are common to subgroups of planetary nebulae and symbiotic stars. It has been known for some time that many of the entries in the symbiotic-star compilations (Allen 1984) also appear in the *Catalogue of Galactic Planetary Nebulae* (Perek and Kohoutek 1967). Most of the objects in common have proven to be examples of the symbiotic phenomenon, but there exist a few cases where definitive classification has proved elusive.

It is one of the objects which has defied unambiguous classification that we will discuss in this paper. We present optical and ultraviolet spectra, optical and infrared images, and infrared photometry of He 2-104 (PK 315+9°1), also known as the Southern Crab (Schwarz, Aspin, and Lutz 1989). We use our data and those published by others to derive the physical properties of this object. A comparison of He 2-104 with symbiotic Miras, with OH/IR stars that have extended structures, and with bipolar and/or young planetary nebulae will provide some interesting clues about evolutionary links between these various classes.

2. Optical and Ultraviolet Spectra

We observed the optical spectrum of He 2-104 at CTIO on three occasions: with the SIT Vidicon at the 1.5-m telescope on 1984 April 29–30 and 1985 May 11–12 and with the 2D-Frutti on the 1-m telescope on 1986 March 13–14. The last spectrogram is the deepest by far and is the best photometrically. All of the observations utilized a 4 arc second wide slit centered on the bright central region of He 2-104. The Vidicon observations covered the wavelength region from 3850 Å to 6850 Å with a resolution of approximately 10 Å. The data were calibrated by using standard stars chosen from Stone and Baldwin (1984) and were reduced with the TVRED software on the MV8000 computer at La Serena. For the 2D-Frutti data, the observing and reduction procedures are the same as for the study of He 2-99 by Kaler *et al.* (1989). The 2D-Frutti spectrum is displayed in Figure 1, where the strongest lines are truncated in order to show the rich spectrum of weak emission lines. A number of selected lines are identified in Figure 1, including four weak ones (C II λ4267, [Cl III] λλ5517,37, and [Fe VII] λ5721) in order to show the minimum intensity level to which we worked. The resolution on expansion of the spectrum is notably better than can be shown in this small-scale figure.

The measurements of the optical data are listed in Table 1, where the first and second columns give the wavelengths and identifications. The identifications were taken from Moore (1945), Bowen (1960), and from Allen's (1983) study of the spectroscopically similar object H 1-36. Note the existence of a few unidentified features. The next three columns list the relative line intensities uncorrected for reddening on the scale $I(\mathrm{H}\beta) = 100$ from the 2D-Frutti and SIT observations. The last column shows the filter observations from Shaw and Kaler (1989). These were made in the first order without an order-blocking filter, and hence Hα and other red lines with $\lambda \geq 6300$ may not be calibrated properly. The comparison in Table 1 shows no serious effect, however, and we will use the 2D-Frutti observations in some of the calculations of nebular parameters.

There is no convincing evidence for temporal variations in the relative intensities or absolute fluxes over the last several years. The differences between the observed values can be explained by photometric errors and nebular stratification combined with errors introduced by using different apertures. Shaw and Kaler (1989) found $\log F(\mathrm{H}\beta) = -11.73$, which is in good agreement with the SIT observations (-11.80) and the value of -11.76 found by Gutiérrez-Moreno, Moreno, and Cortés (1986). The 2D-Frutti observations give $\log F(\mathrm{H}\beta) = -11.54$, which should be somewhat low because the slit excluded some of the nebula. Despite the apparent lack of variations in the optical spectrum, this object is worth further

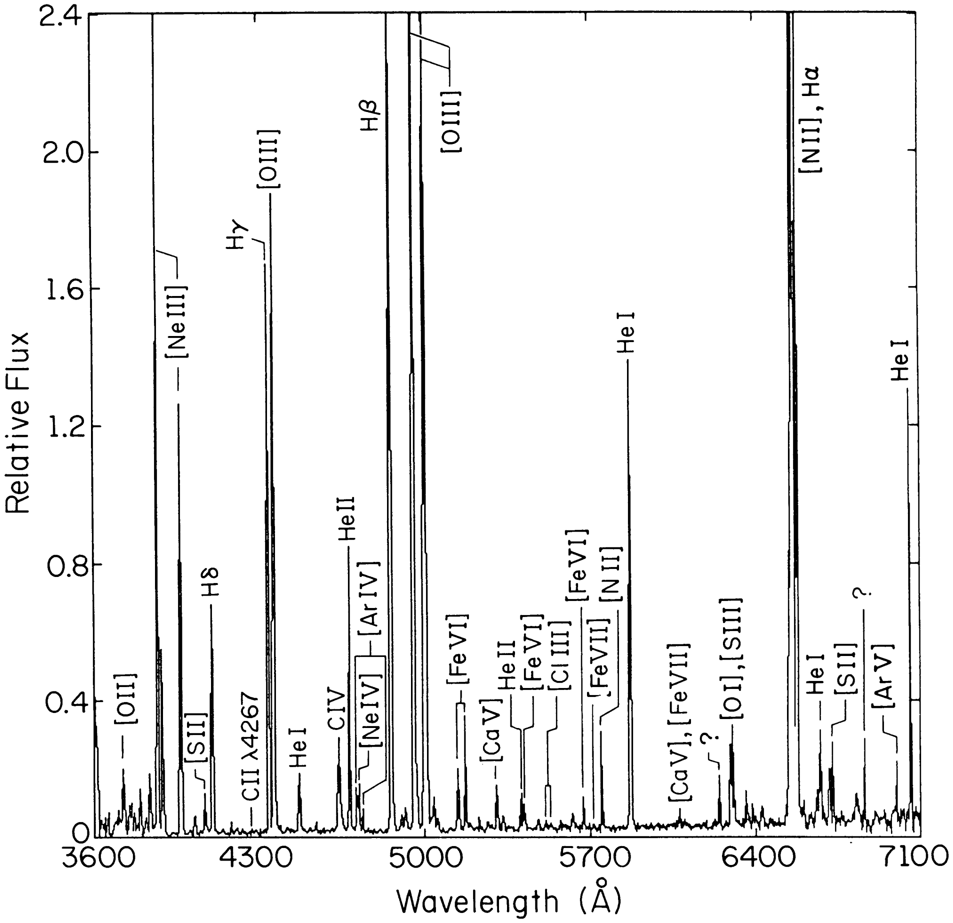

FIG. 1–The optical spectrum of He 2-104.

monitoring. The R Aquarii nebula, to which He 2-104 displays some similarity, is known to be variable by up to at least 0.42 in log $F(\mathrm{H}\beta)$ (Kaler 1981).

The spectrum shows the strong [O III] λ4363 emission and the steep Balmer decrement that are characteristic of high-density, reddened objects. At the same time, the doublets of [S II] and [O II] apparently arise in regions of lower density (see Section 6). The ionized species found in the spectrum range from low ([O I], Si II) to very high (He II, [Fe VII]), as is found in a number of symbiotic stars (Allen 1984).

The spectrum of He 2-104 has much in common with the spectrum of the symbiotic Mira H 1-36, and a comparison of our line intensities with those published for H 1-36 by Allen (1983) is shown in Figure 2. Broadly, our results are in good qualitative accord with his over nearly four decades of intensity. The scatter and systematic differences may be ascribed to errors in reddening and to genuine differences in ionization level. H 1-36 is clearly the more highly ionized of the two: The relative He II λ4686 line intensity is twice that of He 2-104. More telling are the forbidden iron lines. [Fe V], [Fe VI], and [Fe VII] are indicated in Figure 2 by crosses, filled circles, and X's, respectively, and the systematic shift is very obvious. The highest ionization species are much stronger in H 1-36: The average line-strength ratios I(He 2-104)/I(H 1-36) are 6, 1.5 (excluding [Fe VI] λ4967, which is peculiar), and 0.06, where the λ6087 line is assumed to be all [Fe VII].

We observed He 2-104 at low resolution with the International Ultraviolet Explorer satellite on 1985 April 24 and 25. The observations consist of an 80-minute, large-aperture LWP exposure (LWP 5810) and a 160-minute, large-aperture SWP exposure (SWP 25770). A plot of the ultraviolet spectrum is shown in Figure 3. The data were reduced at the Goddard Space Flight Center RDAF. The emission-line fluxes are included in Table 1. These fluxes should be used in place of those published by Lutz (1988) which are erroneous.

In principle, it is necessary to scale the ultraviolet fluxes to the optical, since different aperture sizes were used. From the contours generated from images of He 2-104 (see Section 3), we estimate that the 10 by 20 arc second IUE aperture accepts approximately 95% of the light from the bright section of the nebula. Because of the steep decline of the contours, even the 4 arc second wide 2D-Frutti aperture accepts about 85% of the light. Pho-

TABLE I

The Spectrum of He2-104

λ	ID	I(2dF)	I(SIT) 1984	I(SIT) 1985	I (Filter)	λ	ID	I(2dF)	I(SIT) 1984	I(SIT) 1985	I (Filter)
1550	CIV	24.2	...	...	...	5007	[OIII]	268	265	291	...
1640	HeII	12.4	...	...	...	5041	SiII	1.5	...	...	...
1747	NIII]	7.4	...	...	...	5056	SiII	0.6	...	...	...
1892	SiIII]	3.9	...	...	...	5146	[FeVI]	4.3	5.8	6.4	...
1909	CIII]	21.9	...	...	...	5176	[FeVI]	8.2	9.1	10.2	...
2730	HeII	4.2	...	...	...	5192	[ArIII]	0.28	...	...	...
2798	MgII	19.9	...	...	...	5199	[NI]	0.29	...	...	...
2830	HeI	7.4	...	...	...	5234	[FeVI]	0.8	...	...	...
3047	OIII	6:	...	...	...	5270	[FeIII]	0.6	...	...	...
3132	OIII	46.9	...	...	...	5309	[CaV]	2.7	...	...	...
3726	[OII]	3.1	...	...	...	5335	[FeVI]	0.9	...	...	...
3729	[OII]	1.7	...	...	...	5411	HeII	2.5	2.0	...	...
3750	H12	1.9:	...	...	...	5424	[FeVI]	1.9	...	...	...
3760	OIII	2.1	...	...	...	5485	[FeVI]	0.6	...	...	...
3771	H11	1.1	...	...	...	5517	[CℓIII]	0.26	...	...	...
3798	H10	3.3	...	...	...	5537	[CℓIII]	0.20	...	...	...
3819	HeI	1.3	...	...	...	5577	[OI]	0.5	...	...	...
3835	H9	4.4	...	...	...	5631	[FeVI]	1.2	...	...	...
3868	[NeIII]	84	57	96	...	5677	[FeVI]	2.2	...	...	...
3889	H8,HeI	15	17	41	...	5721	[FeVII]	0.7	...	...	...
3969	H7,[NeIII]	27	34	25	...	5754	[NII]	4.7	4.6	5.7	...
4026	HeI	1.4	...	...	...	5801	CIV	0.2	...	...	...
4068+76	[SII]	3.7	5.2	...	...	5876	HeI	33.1	31.2	39.5	...
4101	Hδ	17.8	20.8	26.8	...	6087	[CaV]	1.4	...	...	...
4143	[FeV]	0.6	...	...	...		[FeVII]	...	...	...	...
4181	[FeV]	0.77	...	...	...	6252.2	...	4.1	...	...	...
4267	CII	0.13:	...	...	...	6300	[OI]	6.2	11.7	14.0	...
4340	Hγ	35.5	50.6	36.3	...	6312	[SIII]	5.7	...	...	...
4363	[OIII]	43.9	51.3	47.8	...	6363	[OI]	1.3	...	...	...
4471	HeI	4.1	3.3	7.0	...	6371.7	...	1.0	...	...	...
4541	HeII	0.8	...	...	...	6396	[MnV]	1.6	...	...	...
4571	MgI	0.6	...	...	...	6406	HeII	0.9	...	...	...
4634	NIII	2.6	...	...	...	6435	[ArV]	1.5	...	...	...
4640	NIII	6.0	11	13.4	...	6563	Hα	787	987	...	867
4647	CIV	1.1	...	...	...	6584	[NII]	58.8	80.9	...	71
4658	CIV,[FeIII]	0.5	...	...	...	6606.5	...	0.8	...	...	...
4686	HeII	19.5	20.8	22.3	20	6636.6	...	3.0	...	...	...
4711	[ArIV]	3.2	...	...	...	6678	HeI	7.0	11.5	...	...
4724	[NeIV]	3.2	7.1	8.9	...	6717	[SII]	3.7	7.0	...	...
4740	[ArIV]	1.5	...	...	...	6731	[SII]	5.1	9.6	...	...
4861	Hβ	100	100	100	100	6831.7	...	2.4	...	...	...
4905	[FeIV]	1.0	...	...	...	6867.8	...	5.9	...	...	...
4921	HeI	1.6	...	...	...	7005	[ArV]	2.5	...	...	...
4959	[OIII]	97	101	104	120	7065	HeI	26	5.2	...	...
4967	[FeVI]	8.1	...	...	...	7136	[ArIII]	...	22.9	...	...

tometric differences as well as uncertainty in the reddening mask the small corrections, so we adopted the IUE fluxes as observed and scaled them directly to those from Shaw and Kaler's (1989) filter observations so as to place them on the scale $I(\mathrm{H}\beta) = 100$. The fluxes can be recovered by using $\log F(\mathrm{H}\beta) = -11.73$.

3. CCD Images and Velocity Studies

CCD images were obtained of He 2-104 with a TI chip on the CTIO 0.9-m telescope. Hα and [O III] images were obtained in May 1986 and [N II] and He II images in April 1988, all under photometric sky conditions. Exposures in [O III] and [N II] are shown in Figures 4 and 5, respectively. The orientation of the prints is that north is up and east is to the right. The [O III] image was obtained with the 5007/20 filter in an exposure time of 400 seconds with seeing estimated to be 1.5 arc seconds; the [N II] image is from a 2400-second exposure with a 6584/15 filter and 1.5 arc second seeing. The Hα image obtained at CTIO is similar in appearance to the [O III] image so it is not reproduced here. However, Schwarz *et al.* (1989) obtained Hα and [O III] images under better seeing conditions. They find that the brightest part of the nebula is slightly more extended on the Hα image and that the Hα image shows an extra jetlike structure that does not show up on the [O III] image. The processing for our images was done by using the AIPS software on the Academic VAX 785 computer at Washington State University.

He 2-104 consists of a bright nebula which has a diameter of approximately 12″ with faint outer lobes extending out to a total diameter of about 75″. The [N II] image shows more clumping than Hα or [O III]. The He II image is stellar and is not reproduced here. In order to get more detail on the faint outer structures, an exposure was taken with the [O III] filter such that the bright nebulosity was positioned just outside the field covered by the chip. This

1200-second exposure is shown in Figure 6. The bipolar lobes are filled in with faint, clumpy structures that are reminiscent of features associated with Herbig-Haro objects and with bipolar outflows from other types of young stellar objects. The images shown in this paper are similar to those published by Schwarz *et al.* (1989), though slightly different filters were employed in their investigation.

In addition, Schwarz *et al.* (1989) obtained intermediate resolution spectra of He 2-104 with the Boller and Chivens spectrograph on the 2.2-m telescope at La Silla in May 1988. Their data show that the northern lobe of the nebula has a velocity of -36 ± 18 km s^{-1}, the central bright region has a velocity of -139 ± 12 km s^{-1}, and the southern lobe has a velocity of -235 ± 15 km s^{-1}. Thus, the lobes are expanding away from the central regions with velocities that are substantial. Such velocity features are seen in both symbiotic stars and planetary nebulae (Weinberger 1989). The cause of the high velocities observed in the nebular lobes will be discussed as part of the model presented in Section 7.

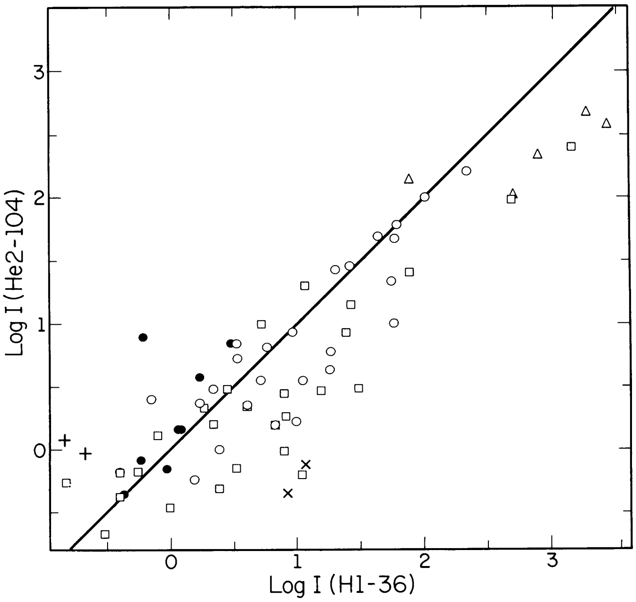

FIG. 2–The spectrum line intensities of H 1-36 versus those of He 2-104.

4. Infrared Observations

Infrared fluxes were obtained in the wavelength bands *JHKLM* at ESO in March 1988. Our results are presented along with other values found in the literature (Allen 1982; Persi *et al.* 1987) in Table 2. Whitelock (1987) has found He 2-104 to have a Mira-like variable with a period of 400 days. In a $(J-K)$ versus $(K-L)$ diagram where the infrared colors have been corrected for interstellar extinction (Whitelock 1987), He 2-104 has colors similar to those of H 1-36 (Allen 1983), and both of them lie near a line that represents the colors of Miras with stellar temperatures of 2500 K in combination with an 800 K dust shell. The amount of circumstellar reddening indicated at K is about 1.5 mag. Persi *et al.* (1987) note that the $(J-H)$ and $(H-K)$ colors are those of a category of dusty objects which includes some of the D-type symbiotic objects and some peculiar planetary nebulae such as Mz 3 and SwSt 1. In a log-log plot of the ratios of the 25-micron flux to the 12-micron flux versus the 60-micron flux to the 25-micron flux (Whitelock 1987), He 2-104 occupies an extreme position, far from the locations of ordinary or symbiotic Miras, with the exception of He 2-390.

Spectroscopy in the near-infrared has yet to uncover any emission features. Roche, Allen, and Aitken (1983) obtained spectra in the 8 to 13 micron region and found a featureless spectrum that is characteristic of warm dust. Another symbiotic Mira, BI Crucis, is known to have a similar spectrum, as do some planetary nebulae (Aitken and Roche 1982). Many of the symbiotic Miras do show a feature at 3.3 microns and silicate emission features at

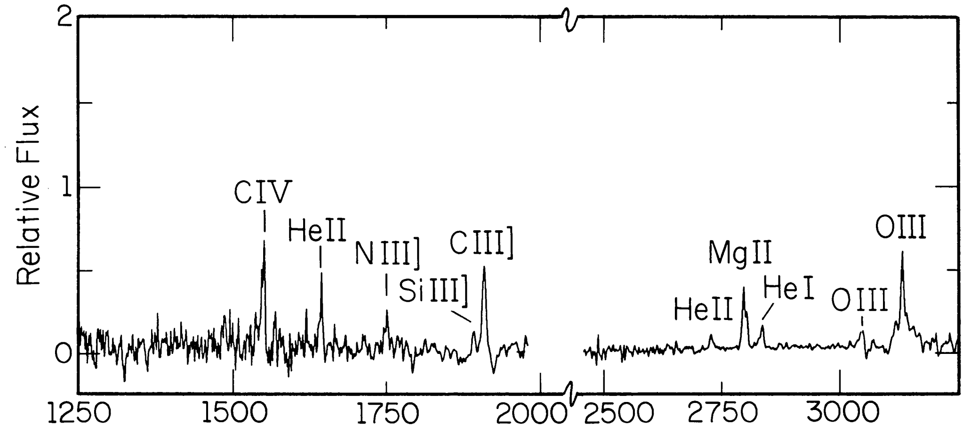

FIG. 3–The combined SWP-LWR spectrum of He 2-104.

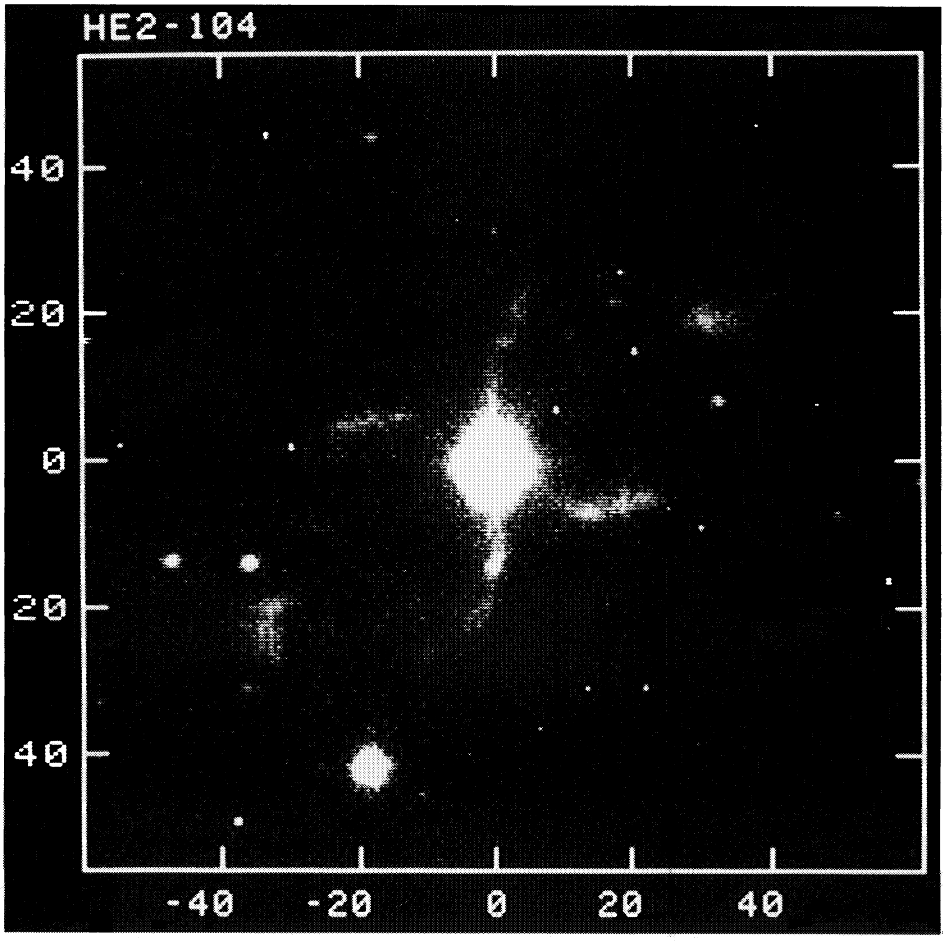

FIG. 4–The [O III] image of He 2-104.

longer wavelengths (Whitelock 1987). Peculiar bipolar planetary nebulae such as Mz 3 show silicate features (Roche 1987), so the symbiotic Miras are not the only objects to exhibit these infrared lines.

The infrared observations of He 2-104 present an ambiguous picture. A compelling observation is the presence of a 400-day period in the infrared. On the other hand, the infrared colors are sufficiently different from other symbiotic Miras and similar enough to some peculiar planetary nebulae to make the evolutionary stage of this object uncertain. He 2-104 does show a similarity in its overall energy distribution in the infrared to OH231.8+4.2 (Reipurth 1987). Possible evolutionary connections between these two objects will be discussed in Section 7.

5. Extinction and Distance

By using the filter intensities for Hα and Hβ and Brocklehurst's (1971) recombination theory, we obtain c (the logarithmic extinction at Hβ, as based on the Whitford (1958) reddening curve) equal to 1.45. However, from the 2D-Frutti Hγ and Hδ intensities we find $c = 0.90$ and 0.85 respectively, for a mean value $\langle c \rangle = 1.05$. The large spread suggests that the object may be optically thick in the Balmer lines. If we apply Cox and Mathews' (1969) analysis to the Hα (filter), Hβ, and Hγ (2D-Frutti) data we find $c = 1.14$, τ (Hα) = 6.5; then from this value of τ and the Hβ, Hγ, and Hδ intensities from the 2D-Frutti observations we consistently derive $c = 1.09$. As a check on these values we calculated the ratio of the reddening-corrected He II λ1640 flux (using the reddening function of Savage and Mathis (1979) and $\langle c \rangle = 1.12$) to that of He II λ4686. The resulting value of 11.9 is above the recombination range for normal nebular temperatures and densities as calculated by Seaton (1978). At 10,000 K, $\log N_e = 3$, the ratio should be 6.5, escalating only 7.6 at 20,000 K, $\log N_e = 6$. If we adopt a theoretical value of the helium-line ratio of 7.0, then c(He II) = 0.92, still reasonably close to the optical values. Given the uncertainties inherent in the intensities and in the comparison of data from two instruments with different apertures, we conclude that the ultraviolet scaling is reasonable and adopt it for further analysis. If we then average the two optical extinctions based on Cox and Mathews' (1969) calcula-

FIG. 5–The [N II] image of He 2-104.

tions and the ultraviolet/optical value from He II, we again derive $\langle c \rangle = 1.05$, which we will use hereafter.

The interstellar extinction constant of $c = 1.05$ leads to $A_V = 2.23$ mag, considerably above that of 0.5 mag estimated from the galactic dust distribution by Whitelock (1987). However, her value seems low, given the distance of 4.7 kpc that is quoted in her paper. An object with the galactic latitude and longitude of He 2-104 ($\ell = 315°$, $b = +9°$) should suffer considerably more interstellar extinction if it were that distant. Our value gives an interstellar extinction at K of about 0.08 mag, whereas Whitelock (1987) estimates a value of 0.00 mag. The large extinction for the star of $A_K = 1.5$ mag again suggests thick circumstellar dust that does not extend far into the nebula. The distance given in Whitelock's (1987) paper would give sizes for each lobe of the nebula of about 1 pc, which would be very large for a planetary nebula.

Gutiérrez-Moreno *et al.* (1986) estimated a distance of 6.32 kpc based on the Cudworth (1974) distance scale, which just exacerbates the problem of having improbably large structures. Schwarz *et al.* (1989) estimate the distance to be 800 ± 300 pc by using several independent methods of analysis. In that case, the size of each nebular lobe would be about 0.15 pc, which is fairly typical of planetary nebulae. However, our value of $c = 1.05$ ($A_V = 2.23$ mag) appears to be unusually large for an object that appears to be less than 1 kpc away. Given the large uncertainties in the distance, we will continue to use $c = 1.05$ in deriving the physical properties. A more accurate distance would enable us to improve our analyses considerably.

6. Physical Properties

Analysis of the emission-line spectrum is difficult because of the large differences in the temperatures and densities found within the system, as evidenced by the wide range of ionization and by examination of various line ratios. All of our analyses apply to the bright central regions of the nebula. The emission from the faint outer lobes is likely due primarily to radiation from shocked gas, and we do not include them in this study. We see the same phenomena here that were described so vividly by Allen (1983) for H 1-36. Briefly, the auroral forbidden lines are coming from a region of much higher density than are the nebular lines, and no unique solution of electron density and temperature is possible. We attempt only a crude analysis here where we adopt the target areas and transition probabilities cataloged by Mendoza (1983) supplemented with new Einstein A values for [O II] from Zeippen (1987) and new collision strengths for [Ar IV] and [Cl III] from Zeippen, Butler, and Le Bourlot (1987) and Butler and Zeippen (1989), respectively. Further details about the methods of analysis for the nebular lines are given by Kaler (1985).

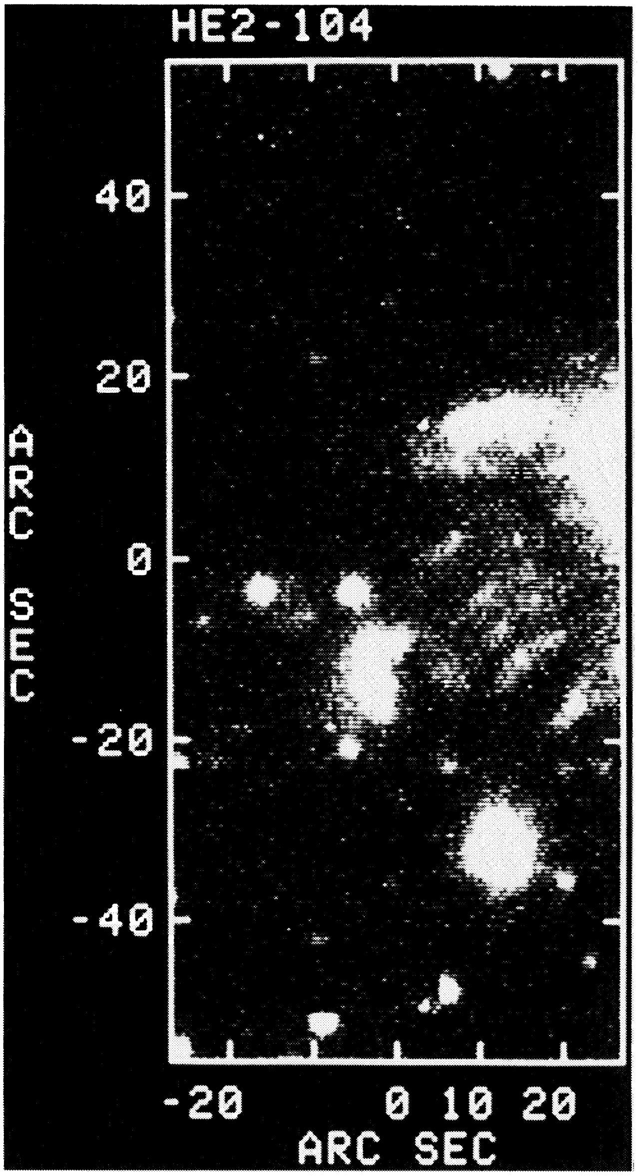

FIG. 6–The [O III] image of the outer lobe of He 2-104.

TABLE 2
Infrared Observations

Band	Allen	Persi et al.	This Paper
J	11.00	10.56	10.7
H	8.56	8.48	8.7
K	6.80	6.64	6.9
L	4.74	4.20	4.5
M			3.9

We have available all four standard p^3 density diagnostics, the nebular doublet ratios from (in order of increasing ionization potential): [S II], [O II], [Cl III], and [Ar IV]. The [S II] lines are strong and easily resolvable. The [O II] features are also strong but closely blended, and we resolve them by fitting a pair of Gaussians, which is very uncertain. The [Cl III] lines are very weak, just above the noise (see Fig. 1), but λ5537 is clearly notably stronger than λ5517. The [Ar IV] doublet is prominent, but λ4711 is blended with He I λ4713, which was removed by assuming that λ4713 is 10% the strength of He I λ4471. This procedure again increases the error. At an electron temperature of 10,000 K, [S II], [O II], [Cl III], and [Ar IV] give, respectively, log $N_e = 3.25, 3.4, 2.7$, and ≤ 2.0. The [Ar IV] λ4711/λ4740 ratio is actually above the theoretical limit, probably because of the large errors associated with these lines. A change in temperature has only a negligible effect on the densities. It is clear that there is stratification of densities. We will attempt to incorporate this general result in a model for He 2-104 in Section 7.

When we try to interpret the auroral lines [O III] λ4363 and [N II] λ5754 with these densities, we get anomalous results similar to those seen in Allen's (1983) Figure 1 for H 1-36. The [O III] λ4363/(λλ4959,5007) intensity ratio is actually higher than is theoretically possible on the basis of any electron temperature, and the analogous [N II] ratio gives 32,000 K. In order to bring the [N II] ratio down to a value that corresponds to a temperature of below 20,000 K, the density must be about 5×10^4 cm^{-3}, and the [O III] value cannot be brought down to any reasonable numbers. We also see something of the same effect in the [Ar III] λ5192 line. If combined with the SIT Vidicon intensity for λ7136, we get $T_e \approx 20{,}000$ K at the lower densities. A better evaluation of the electron temperature might come from the C III] λ1909/C II λ4267 intensity ratio, since the semiforbidden line is much less sensitive to collisional deexcitation. Using Kaler's (1986) modified curve we find $T_e \approx 16{,}000$ K. The value may actually be higher because the identification of the C II line is tentative and the intensity quite uncertain. We can continue to explore the electron temperature with the nebular lines alone. At higher temperatures, O/H from the nebular lines is unrealistically low (0.4×10^{-4} at 15,000 K). In order to raise it to a value that is reasonably standard for planetaries, say 3×10^{-4}, T_e must be as low as 8000 K.

Consequently, we would expect the electron temperature to be between about 8000 K and 16,000 K. In this range, the Ne^{3+}/H ratio, derived from the transauroral [Ne IV] λ4724 blend, is one to two orders of magnitude too high. Thus, it is fair to assume that of all the auroral (or transauroral) lines, those that arise from the ^1S state of the p^2 or p^4 configurations of the ^2P state of the p^3 configuration, are much too bright relative to the nebular lines. It is obvious that we are dealing with at least a two-tiered structure in which the auroral lines come from a high-density region where the nebular lines are suppressed, and the nebular lines come from a low-density zone. Further analysis is not warranted by the observations.

What can we say about the chemical composition? If we use $T_e = 8000$ K and $N_e = 2 \times 10^3$ cm^{-3}, which come from nebular lines alone, then N/O, also from nebular lines (from the [N II] λ6584/[O II] λ3727 intensity ratio), is 0.55, well above the solar value of 0.1 (Ross and Aller 1976). At 10,000 K (at which O/H = 1.2×10^{-4}), N/O is 0.86, and, at 16,000 K, N/O is 1.6. At 16,000 K, the temperature given by the C^{+2} lines, and $N_e = 2 \times 10^3$ cm^{-3}, the C/O ratio from C II λ4267 and Kaler's (1983) algorithm is 2.2, notably greater than the solar value of 0.6 (Ross and Aller 1976). From the ultraviolet lines (C III] λ1909 and C IV λ1550) and Aller's (1984) formulation, we find C/O = 2.5, assuming all the carbon to be in C^{+2} and C^{+3}. At 8000 K, however, C/O from λ4267 drops to 0.28 below solar, and the value derived from the ultraviolet lines climbs to an absurd value of 80. The indication is that the electron temperature is closer to the higher value, so that N/O and C/O are elevated by factors of about 7 and 4, respectively. Even if T_e is lower, N/O is still rather high. If T_e were as high as 20,000 K, then N/O climbs to about 2.0 and C/O (from the ultraviolet lines) falls to 1.2, still double the solar value. The ultraviolet lines may be poor choices for analysis because of internal dust in the nebula (see Harrington *et al.* 1982). Both the carbon and the nitrogen abundances are obviously affected by error in extinction. In order to bring N/O down to the solar value, however, the extinction would have to be $c \approx 2.0$, far higher than the value that we find from interpretations of the hydrogen lines or those found in other studies (Schwarz *et al.* 1989). These results are made all the more uncertain because we cannot evaluate in detail the temperature and density gradients in the regions where the nebular lines arise.

The He/H ratio, fortunately, is much less sensitive to temperature, density, and extinction effects. At T_e = 16,000 K and $N_e = 2 \times 10^3$ cm^{-3}, $He^+/H^+ = 0.109$ (from He I λ4471, and λ5876, the effective recombination coefficients of Brocklehurst (1972), and the collisional corrections given by Clegg (1987)), $He^{+2}/H^+ = 0.020$, and He/H = 0.13. The He I λ6678 line was excluded from the analysis because of a possible calibration error. The He/H ratio is sufficiently close to solar so as not to excite interest. The nonzero optical depth in the Balmer lines discussed in Section 5 compromises abundances relative to hydrogen. However, the reasonable He/H suggests that the problem is not too severe.

A further diagnostic of the physical nature of He 2-104 comes from the ultraviolet C III] and Si III] lines. Feibelman and Aller (1987) use a plot of the logarithm of the ratio of the fluxes of the C III] λ1909 and Si III] λ1897 lines versus N_e to discriminate between planetary nebulae and symbiotic stars. Using $N_e = 10^3$–10^4 cm^{-3} as appropriate to the nebular emission-line spectrum and the logarithm of the observed ratio, 0.75, He 2-104 fits into a part of their diagram that is populated with bipolar planetary nebulae such as NGC 6302 and M 2-9, both of which are known to have highly dusty central regions (see Lester and Dinerstein (1984) and Balick (1989), respectively), and with classical low-excitation young planetaries such as IC 418. Even if densities of 10^5–10^6 cm^{-3} were more appropriate for the region in which the ultraviolet lines originate, the value of 0.75 is higher than that found in the symbiotic stars that have been observed with IUE, which includes D-type symbiotics such as HM Sagittae, V1016 Cygni, and R Aqr.

7. Discussion

Our results, as well as the studies of others, show that He 2-104 is a complicated object. It has what seems to be a pulsating Mira variable in combination with a hot star that is producing extreme conditions of photoionization. A summary of the physical properties is given in Table 3.

To interpret the evolutionary stage, we must examine a variety of possible phenomena. First, there is the question of whether we are dealing with a single star or a binary system. Second, we must compare the characteristics of He 2-104 with those of D-type symbiotic stars, OH/IR stars that are known to have extended structures, and protoplanetary and/or young planetary nebulae. The process of doing these comparisons is not as straightforward as it might seem at first. For example, bipolar structures are being found in increasing numbers among objects in the late stages of stellar evolution. Bipolar structures are common among planetary nebulae (Zuckerman and Aller 1986; Balick 1987) and are found around at least one OH/IR star, OH231.8+4.2 (Reipurth 1987), and around some symbiotic stars (Viotti 1987; Taylor 1988). In order to make at least a rough model of He 2-104, we must make comparisons between its physi-

TABLE 3
Summary of Characteristics

$\alpha(1950)$ = 14 08 53.5
$\delta(1950)$ = -51 12 19
A_V = 2.23 mag
d = 800 ± 300 pc
log F(Hβ) = -11.73
T_e = 8000 - 16,000 K
N_e = 10^3 - 10^4 cm^{-3}
He/H = 0.13
N/O ~ 7 x solar
C/O ~ 4 x solar

cal characteristics and those of other evolved objects which show similar morphologies.

He 2-104 has many things in common with a small but interesting subset of the D-type symbiotic stars. These stars are known to have extended structures (Viotti 1987; Taylor 1988) and they have been found, in addition, to have periodic infrared variability that is interpreted by Whitelock (1987) as arising from the presence of a Mira. R Aqr, HM Sge, and V1016 Cyg show both of these phenomena, with respective periods of 387, 540, and 460 days (see Whitelock 1987 for references to detailed studies).

There are some striking similarities between He 2-104 and the OH/IR star, OH231.8+4.2. This object is believed to be either a single star ejecting a planetary nebula or a binary system in which one of the stars has been losing a lot of mass and is just about to eject a planetary nebula (Reipurth 1987). The high velocities in the lobes (about 200 km s^{-1}) and the bipolar morphology are reminiscent of features found in He 2-104. In addition, in both objects condensations have formed where the outflow hits matter that could be representative of either the ambient interstellar medium or the previously ejected red-giant wind. However, there are some important differences between the two objects. In He 2-104 the central regions of the nebulosity are bright and highly ionized, whereas the bulk of the material in OH231.8+4.2 has low ionization (Cohen *et al.* 1985). Monitoring of the infrared intensity (Feast *et al.* 1983) and the OH-maser intensity (Bowers and Morris 1984) show variability on a time scale of about 650 to 680 days in the OH/IR star. None of the D-type symbiotics is known to have maser emission.

Morris (1987) has proposed a binary model for the creation of bipolar circumstellar shells, and we have adapted his basic ideas to formulate a schematic model for He 2-104. Our proposed model is shown in Figure 7. Basically, the system consists of a red giant in the Mira stage with a hot companion. The Mira is obscured by dust and can be observed only in the infrared. The hot companion is faint and/or obscured by dust and does not show up directly in the IUE spectra. Because of the binary system the mass lost from the Mira has formed a disk around the system generally, and some of the material lost has accumulated in a high-density accretion disk in

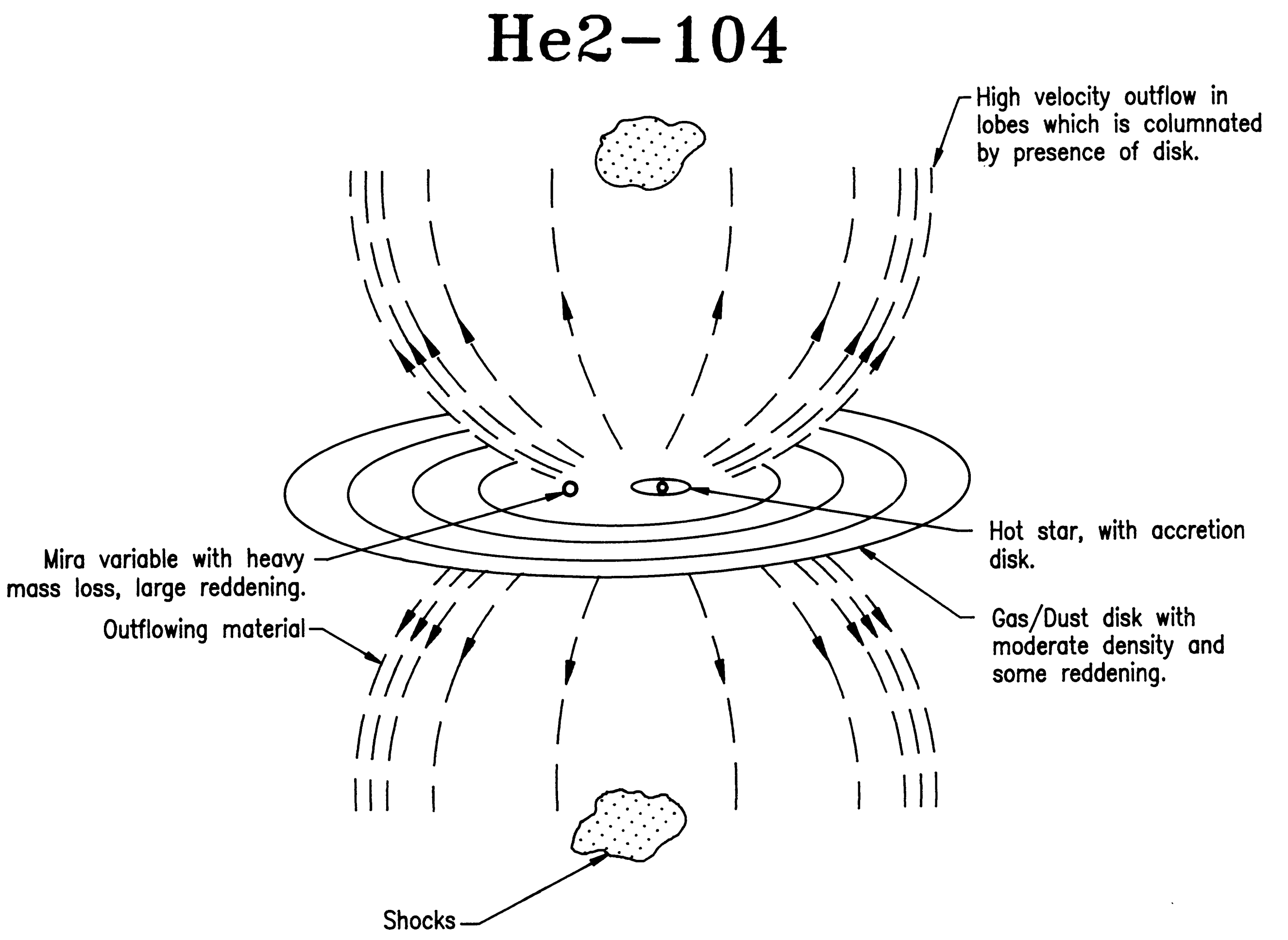

FIG. 7–The model of He 2-104.

the vicinity of the hot star. The hot star has a wind that is interacting with the material in the accretion disk, but its outflow is constrained both by the accretion disk and by a larger disk that surrounds the system. The larger disk is relatively low density and is ionized to a moderate degree by the hot star. The accretion disk and its immediate environment are the source of the high-ionization potential radiation. The "crab legs" are far enough away from the hot source that their spectrum comes from a combination of photoionization and shock. The high-velocity "jets" come from the region of the hot star. Out at the end of the bipolar structures we see the interaction of the jet hitting the interstellar medium or material that was previously lost from the binary system.

This model for He 2-104 is neither that of a symbiotic star nor that of a planetary nebula. We believe that it is an object in transition between the two stages of evolution. What will He 2-104 look like later on? We would expect that the continuing mass loss from the Mira would result in a thicker disk. Eventually the Mira will release its outer atmosphere in what would be recognized as the major planetary nebula birth event. Angular momentum that was present in the Mira will get transferred to the disk. The two stars in the binary system will get closer together. Because of the constraining large disk, the bipolar morphology will be preserved. The nebulosity will end up with two hot sources of ionization, perhaps resulting in butterfly-shaped, highly ionized planetary nebulae such as NGC 6302 or NGC 2240.

Do we see phenomena in planetary nebulae that can be interpreted as the legacy of the events taking place now in He 2-104? The answer is a definite "yes", but these phenomena are found only among a rather restricted subset of bipolar planetary nebulae. This is what we expect if He 2-104 represents a way for some symbiotic stars to make the transition to the planetary nebula phase. High velocities have been found in the lobes of bipolar planetary nebulae such as NGC 6302, Mz 3, M 2-9, and He 2-111 (see review by Weinberger 1989). Dusty torus structures exist in the central regions of these objects (Balick 1989). Further, their densities are stratified with the central regions exceeding 10^5 cm^{-3} (Balick 1989). The infrared colors of Mz 3 (Whitelock 1985) are similar to those of He 2-104, and both are atypical for planetary nebulae or symbiotic stars.

One thing that is not similar between He 2-104, on the one hand, and Mz 3 and M 2-9, on the other, is that the latter two objects are of relatively low ionization. We would explain this by saying that Mz 3 and M 2-9 have reached a phase where the dusty torus is sufficiently opaque so as to prevent the radiation from ionizing the gas in the outer parts of the torus region. As the planetary nebula from the star that was formerly a Mira variable within He 2-104 expands, the dust torus will be pushed out, much of the dust will be destroyed or dissipated by ionizing radiation, and the nebula will again become highly ionized. NGC 6302 is an example of a peculiar bipolar planetary nebula that might fit this portion of the scenario. NGC 6302 has a substantial infrared disk that can be interpreted as warm dust (Lester and Dinerstein 1984). It has outflows of material from the central regions as seen in both low-ionization (less than 200 km s^{-1}) and high-ionization (up to 800 km s^{-1}) emission lines (Meaburn and Walsh 1980). The central star has a temperature greater than 2×10^5 K (Ashley and Hyland 1988; Kaler and Jacoby 1989).

To summarize, we have determined that the physical characteristics of He 2-104 do not accord well with either the standard models of planetary nebulae or symbiotic stars. We propose that He 2-104 represents a transition phase whereby the Mira member of a D-type symbiotic star system is becoming a peculiar bipolar planetary nebula. In order to make further progress on this model, further investigations of D-type symbiotic stars for extended structures and infrared variability are necessary. In addition, more high-resolution optical observations are needed to determine velocities in various regions of bipolar objects.

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