He 2-104: A Link Between Symbiotic Stars and Planetary Nebulae?[1]

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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 upon the previously-ejected red giant wind and/or the ambient interstellar medium.

I. 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 upon 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 have emission lines from only moderately ionized atomic species.

With planetary nebulae, a number of subdivisions can be made depending upon 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 (1985) 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 1989, 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 (butterfly-shaped) 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 1989, 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.

II. 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 April 29-30, 1984 and May 11-12, 1985, and with the 2D-FRUTTI on the 1-m telescope on March 13-14, 1986. The last spectrogram is the deepest by far and is the best photometrically. All of the observations utilized a 4 arcsecond wide slit centered on the bright central region of He 2-104. The Vidicon observations covered the wavelength region from 3850 to 6850 A with a resolution of approximately 10 A. The data were calibrated by using standard stars chosen from Stone and Baldwin (1983) 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] $\lambda\lambda$5517,37 and [Fe VII] λ5721) in order to show the minimum intensity level to which we worked. The resolution upon 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(Hβ) = 100 from the 2D-FRUTTI and two SIT observations. The last column shows the filter observations from Shaw and Kaler (1989). Comparison of the three sets of data shows reasonable agreement. The 2D-FRUTTI observations 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 red 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 due to different apertures. Shaw and Kaler (1989) found log F(Hβ) = -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), both of which used apertures large enough to include the flux from the entire bright nebulosity. The 2D-FRUTTI observations give log F(Hβ) = -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 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(Hβ) (Kaler 1981).

The continuum level in the optical is very low and there is no direct evidence for either a hot or a cool star based upon the optical continuum data alone. However, in the infrared, Whitelock (1987) has found Mira-type variability with a period of about 400 days.

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 VI). 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 April 24 and 25, 1985. 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, and the intensities are also plotted in Figure 2. These ultraviolet line 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 III), we estimate that the 10 by 20 arcsecond 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 arcsecond wide 2D-FRUTTI aperture accepts about 85 % of the light. Photometric 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 $I(H\beta) = 100$. The fluxes can be recovered by using $\log F(H\beta) = -11.73$.

The fact that no stellar flux was detected in the ultraviolet is evidence that the central ionizing object is heavily obscured by dust. The analysis of the emission line spectrum and the physical interpretation of the spectra will be discussed in Sections VI and VII.

III. CCD Images and Velocity Studies

CCD images were obtained of He2-104 with a TI chip on the CTIO 0.9-m telescope. Hα and [O III] images were acquired in May of 1986 and [N II] and He II images in April of 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 arcseconds; the [N II] image is from a 2400 second exposure with a 6584/15 filter and 1.5 arcsecond 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) secured 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 jet-like 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 found 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 1989, and by Schwarz, Aspin and Lutz (1989) though slightly different filters were employed in their investigation.

In addition, Schwarz, Aspin and Lutz (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 VII.

IV. 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 fact, the J-H and H-K colors of Mz 3 (Whitelock 1985) are very similar to those of He 2-104. 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. The colors of He 2-104 in such a diagram can be represented roughly by a combination of blackbodies with temperatures of 800 K and 150 K.

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 Cru, is known to have a similar spectrum, as do some planetary nebulae (Aitken and Roche 1982). Many of the symbiotic Miras do show the dust feature at 3.3 microns and silicate emission features at 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 (Schwarz, Aspin and Lutz 1989) to OH231.8+4.2 (Reipurth 1987). Possible evolutionary connections between these two objects will be discussed in Section VII.

V. Extinction and Distance

By using the filter intensities for $H\alpha$ and $H\beta$ and Brocklehurst's (1971) recombination theory, we obtain c (the logarithmic extinction at $H\beta$, as based on the Whitford 1958 reddening curve) equal to 1.45. However, from $H\gamma$ and $H\delta$ we find c = 0.90 and 0.85 respectively, and a mean value c = 1.05. As a check on this value, we calculated the ratio of the reddening-corrected He II λ1640 flux (using the reddening function of Savage and Mathis 1979) to that of He II λ4686. The resulting value of 9.6 is somewhat 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 to 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) =0.93, still quite close to the optical value. Given the uncertainties inherent in the comparison of data from two instruments with different apertures, we conclude that both the optical interstellar extinction and the ultraviolet scaling are reasonable and adopt them for further analysis. We would like to emphasize that our analysis is dependent upon the assumption that the bulk of the hydrogen gas responsible for the emission lines can be characterized by recombination theory.

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 (l = 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 into the nebula.

We note that the distance given in Whitelock's (1987) paper would give sizes for the each lobe of the nebula of about 1 pc, which would be very large for a planetary nebula. Gutiérrez-Moreno, Moreno and Cortés (1986) estimated a distance of 6.32 kpc based upon the Cudworth (1974) distance scale, which just exacerbates the problem of having improbably large structures. Schwarz, Aspin and Lutz (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 the analysis of Section VI.

VI. Physical Properties

Analysis of the emission line spectrum is difficult because of the large differences among 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 catalogued 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 (1988) respectively. Further details about the methods of analysis for the nebular lines are given by Kaler (1985).

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 Figure 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 $\leq$2.0. The [Ar IV] $\lambda4711/\lambda4740$ 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 VII.

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] $\lambda4363/(\lambda4959,\lambda5007)$ 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 x 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 semi-forbidden line is much less sensitive to collisional de-excitation. 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 x 10^{-4} at even 15,000 K). In order to raise it toa value that is reasonably standard for planetaries, say 3 x 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 all of all the auroral (or transauroral) lines, those that arise from the ^1S state of the p^2 or p^4 configurations or 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 supressed, and the nebular lines 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 x 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 0.13 (Ross and Aller 1976). At 10,000 K (at which O/H = 1.2 x 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 x 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 1986). From the 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, Seaton, Adams and Lutz 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, Aspin and Lutz 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 the calibration is suspect. The He/H ratio is sufficiently close to solar so as not to excite interest.

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 Sge, V1016 Cyg and R Aqr.

VII. 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. It has a complex nebulosity with regions of both low and high density in the brightest part of the nebula. The high velocities found in the much fainter outer lobes are in sharp contrast to the slower expansion of the bright inner nebula. The infrared colors are peculiar and indicate the presence of dust in the central regions of the system.

Given all these interesting features, it is almost surprising to find that the physical conditions in some parts of the nebula are more-or-less normal. Some regions of the nebula are of lower density than others and there may be a range of electron temperatures also. Compared to solar values, helium has a reasonably normal abundance, nitrogen appears to be enriched and the carbon content may be high. Considering the diverse physical conditions we think we have done about as much as it is possible to do regarding diagnostics from the emission line spectrum, given the relatively low resolution of our spectroscopic observations.

To interpret the evolutionary stage of this object, 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 1985, 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). As was discussed in Section I, there is considerable debate about the cause of these structures. In order to make at least a rough model of He 2-104, we must make comparisons between its physical 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. A few of 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). As noted previously, the optical and ultraviolet emission line spectrum of He 2-104 is very similar to that of H 1-36, another D-type symbiotic star that is not known to have extended structures but is known to have a 450 day period of variability in the infrared (Whitelock 1987). The phenomena exhibited by these few objects are different from those found in most symbiotic stars. No S-type symbiotic stars are known to have extended structures or Mira variables.

There are some striking similarities between He 2-104 and the OH/IR star, OH231.8+4.2, which has an extended bipolar structure (Reipurth 1987). 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. 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 timescale of about 650 to 680 days. Whether or not this observation could be related to the type of variability shown by the D-type symbiotics is not known. 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 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 has relatively low density and is ionized to a moderate degree by the hot star. The accretion disk and its immediate enviornment is 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 lost from the binary system previously. The large disk contains both gas and dust; the Mira itself is the heavily shrouded element in the center of the system.

The model we are proposing for He 2-104 is neither that of a symbiotic star nor 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 is recognized as the major planetary nebula birth event. Angular momentum that was present in the Mira will get transfered 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 2440. Because there is ionization present already due to the hot companion, we would not expect He 2-104 to go through the usual planetary nebula scenario of having a cool central star with a low ionization nebula. The system would always be complex and strange.

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 a subset of symbiotic stars to make the transition to a subset of planetary nebulae. 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 fact 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 x 10^5 K (Ashley and Hyland 1988, Kaler and Jacoby 1989). At the same time, NGC 6302 shows substantial enrichments in He/H and N/O compared to solar values (Aller and Keyes 1981) and thus it is classified as a Type I planetary nebula (Calvet and Peimbert 1983). He 2-111 has a hot central star ($T \geq 80{,}000$ K), but has the unique feature of having both He II λ4686 and [N II] λ6584 emission lines extremely strong in the spectrum (Shaw and Kaler 1989).

Binary central stars in general will not be a help in establishing the veracity of our model because they are associated with a variety of morphologies (Lutz, Balick, Heathcote and Weller 1989). However, the fact that there are short period binary central stars (Bond 1989) shows that the transfer of angular momentum can drive them quite close together. Other properties of planetary nebulae that have been found to be fairly common are shared with He 2-104 and the D-type symbiotics. First, there are some high density planetaries ($N_e = 10^5$-10^6 cm^{-3} which fit well with the densities found in D-type symbiotics. Second, velocities of several hundred km s^{-1} are found in all types of planetary nebulae (Weinberger 1989). Finally, with regard to the condensations seen in the outer lobes of He 2-104, such structures are found commonly in planetary nebula shells, particularly in bipolar structures. Hence, the hypothesis that He

2-104 will eventually become a bipolar planetary nebula is consistent with the physical properties observed in planetaries.

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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TABLE I

The Spectrum of He2-104

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

Table 2

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

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