

PROTO-PLANETARY NEBULAE. II. THE SHOCK-HEATED BIPOLAR NEBULAE GL 618 AND M2-56

ROBERT W. GOODRICH¹

McDonald Observatory, Department of Astronomy, University of Texas, Austin, TX 78712-1083

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ABSTRACT

The two peculiar, very low ionization proto-planetary nebulae GL 618 and M2-56 are studied using long-slit CCD spectroscopy. Previous optical investigations of these objects have analyzed them in terms of photoionization models, although more recent investigations from the radio to IR have identified much of the emission as shock emission. In this work, improved optical spectra of M2-56 and published spectra of GL 618 are compared with the observed spectra of Herbig-Haro (HH) objects and with theoretical shock model calculations published in the literature. It is shown that the spectra of low-excitation HH objects match very well the spectra of GL 618 and M2-56, with the exception of [S II], which is weaker in the proto-planetary nebulae. The shock models indicate the presence of a range of shock velocities from ~ 40 – 100 km s^{-1} , again similar to what is seen in low-excitation HH objects. It is argued that the radio brightening seen in GL 618 is due to the advance of an ionization front into the inner parts of the bipolar lobes, while the lack of detected radio flux from M2-56 indicates that it may be at a slightly earlier evolutionary stage. These objects are probably in transition between the OH/IR stars and more fully developed and photoionized planetary nebulae like M2-9 and M1-91. The presence of shock emission and the absence of substantial photoionization in GL 618 and M2-56 allow us a rare opportunity to study the dynamics of the early mass-loss phase in proto-planetary nebulae, free from the effects of the central star's photoionization energy input.

Subject headings: nebulae: individual (GL 618, M2-56) — nebulae: planetary — shock waves — stars: circumstellar shells

1. INTRODUCTION

Planetary nebulae are nebulae photoionized by hot central stars which have evolved off the asymptotic giant branch (AGB). The transition from AGB to planetary nebula (PN) is thought to include such evolutionary states as the OH/IR stars, so-called proto-planetary nebulae, and young planetaries, the latter usually distinguished by the low temperatures of their central stars. The radical change from red giant to white dwarf, which is encompassed by the intermediate evolutionary states, is one of the most spectacular in stellar evolution, and our understanding of the mechanisms involved must necessarily include a study of the AGB to PN phase.

Mass loss occurs at all stages of the transition process, although the exact number of distinct mass-loss phases is still unclear. In the red giant stage there is a slow (20 km s^{-1}) wind with a mass-loss rate of around $10^{-6} M_{\odot} \text{ yr}^{-1}$. The star next passes through the OH/IR stage, when the mass loss increases dramatically, wrapping the star in an optically thick cocoon of dust and gas. This increase in mass loss may be related to a switch from pulsation in the first-overtone mode to pulsation in the fundamental mode, as described by Jones et al. (1982). The OH/IR stars are very difficult to study using optical techniques because they are often completely invisible behind their dust shells. When the evolving central star becomes hot enough, it ionizes the ejected gas, and at some point a much faster central wind turns on from the surface of the central star. A "superwind" such as that proposed by Renzini (1981) may also contribute to the mass loss.

One might expect a rich variety of interactions between these different winds, and also with the interstellar medium. Early in the evolution the central star will be too cool to photoionize the nebula, and energy input into the nebula must come from another source. One possibility is energy and momentum transfer due to the radiative acceleration of dust grains, such as occurs in the OH/IR stars. A second possibility is shocks, as recently accelerated material impacts other, slower moving material outside of it. Because these shocks are more closely related to the dynamics of the gas, rather than to the condition of the central star as in photoionized nebulae, such a shock stage could provide a better probe of the outflow conditions in the early evolutionary stages.

In fact the bipolar proto-planetary nebulae GL 618 and M2-56 are two such shock-heated objects, as this paper will discuss. Previous work on GL 618 is rather extensive, but optical studies (Westbrook et al. 1975; Schmidt & Cohen 1981) have assumed that photoionization is the energy source of the nebula, and have derived central star characteristics based on this assumption. Abundances in GL 618 were derived by Calvet & Peimbert (1983), also under the assumption of photoionization. These latter authors discuss the possibility that GL 618 might be related to the shock-heated Herbig-Haro (HH) objects found in the vicinities of young pre-main-sequence stars, but decide from their comparisons with HH 1 and HH 32 that the spectral match is not very good. Subsequently, infrared observations of molecular hydrogen by Beckwith, Beck, & Gatley (1984) pointed to the presence of shocked H_2 in the lobes of GL 618, and these authors also point out the similarity between the optical spectrum of GL 618 and that of HH objects. They do not, however, attempt to analyze the optical spectra from that point of view. Goodrich & Bianchi (1989) first performed a comparison of both GL 618 and M2-56 with

¹ Postal address: Department of Astronomy 105-24, California Institute of Technology, Pasadena, CA 91125.

low-excitation HH objects, showing general agreement. More recently Riera (1991) has compared GL 618 with shock models.

M2-56 has been relatively poorly observed. Cohen & Kuhl (1977) presented the first optical spectrum of this faint bipolar, also analyzing it as if it were photoionized. Its optical spectrum is very similar to that of GL 618, and hence it is likely that M2-56 is also a shock-heated nebula. This contention is supported by the lack of observable radio emission from this object (<0.3 mJy at 5 GHz; Aaquist & Kwok 1990). In fact, as the present work shall detail, the optical spectra of both GL 618 and M2-56 are quite similar to those of low-excitation HH objects such as HH 46 and HH 7-11. New observations of M2-56 are presented, and, together with the existing data on GL 618, discussed in the context of excitation by low-velocity shocks.

Subsequent evolution of GL 618 and M2-56 will probably lead to morphologies similar to those of other bipolar planetaries such as M2-9 and M1-91 (e.g., Icke, Preston, & Balick 1989). As discussed by Goodrich (1991, hereafter Paper I), it is likely that these latter bipolars have binary central stars. Since GL 618 and M2-56 are shock-heated, and hence influenced more by the flow interaction than by the central star, it is difficult to say whether or not they, too, are the results of planetary nebula formation in a binary system.

2. OBSERVATIONS

Low-resolution optical spectra of M2-56 were obtained using both the UV Schmidt and all-transmission spectrographs on the 3 m Shane reflector of Lick Observatory (Miller, Robinson, & Goodrich 1988). A high-resolution spectrum centered on $H\alpha$ $\lambda 6563$ was obtained with the large Cassegrain spectrograph on the 2.7 m reflector of McDonald Observatory. The detectors in all three cases were 800×800 TI CCDs with $15 \mu\text{m}$ pixels. All spectra were taken through a $2''$ slit oriented east-west and passing through the star just west of M2-56. Other details, such as the dispersion, exposure times, and wavelength coverage, are provided in Table 1.

Wavelength calibration of the spectra was performed using lamps of neon, helium, argon, mercury, and/or cadmium. The zero point of the high-resolution spectrum was determined by measuring the central wavelengths of the $[O\text{ I}]$ $\lambda\lambda 6300, 6363$ night-sky lines, so that an absolute velocity scale could be defined. The internal accuracy of this velocity scale is $\sim 3.5 \text{ km s}^{-1}$. Absolute flux calibration of all spectra was obtained by observing standard stars from the list of Stone (1977).

Line fluxes were calculated from these spectra by the usual technique of subtracting a local fit to the continuum and integrating the flux under the line. Line ratios with respect to $H\beta$ are used throughout this paper; in the region of overlap between red and blue spectra, the ratios from individual spectra were averaged. The two blends of $H\alpha + [N\text{ II}]$ and $[S\text{ II}]$ $\lambda\lambda 6716, 6731$ were deblended in M2-56W using the high-

TABLE 1
SPECTROSCOPY OF M2-56

Date	Exposure (minutes)	Wavelength Range ($\text{\AA}$)	Dispersion ($\text{\AA pixel}^{-1}$)
1985 Aug 21	30	4091-8397	5.0
1987 Sep 20	30	2882-6090	4.0
1989 Aug 4	60	6162-6869	0.885

TABLE 2
OBSERVED LINE FLUXES FOR M2-56

LINE	WAVELENGTH ($\text{\AA}$)	FLUX ($10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}$)	
		West	East
[O II]	3727	0.96	...
H ζ	3889	0.20	...
H ϵ	3970	0.50	...
[S II]	4071	0.45	...
H δ	4101	0.29	...
H γ	4340	0.70	...
H β	4861	3.29	0.48
[Fe II]	5159	0.73	...
[N I]	5200	1.48	...
[Fe II]	5262	0.58	...
[O I]	5577	0.67	...
Na I	5893	5.56	0.89
[O I]	6300	15.92	0.51
[O II]	6363	5.78	...
[N II]	6548	3.00	0.59
H α	6563	32.7	3.18
[N II]	6583	10.47	1.78
[S II]	6717	5.40	0.39
[S II]	6731	6.82	0.31
[Fe II]	7155	1.57	...
[O II]	7320	7.02	...

resolution spectrum, in which all the lines are completely resolved. In this spectrum the signal-to-noise ratio in the east lobe was insufficient to derive accurate line fluxes, and hence the low-resolution spectrum was used for deblending in M2-56E. Observed line fluxes, uncorrected for reddening, are presented in Table 2, while the spectra themselves are presented in Figure 1.

The proto-planetary nebula GL 618 has been well studied by a number of authors, and the line fluxes used in this paper are from Schmidt & Cohen (1981). The line fluxes reported in Westbrook et al. (1975) are in excellent agreement with those of Schmidt & Cohen for the brighter (east) lobe. The fluxes are not reproduced in Table 2 but are included in Table 3 after a correction for reddening described in the next section.

An image of M2-56 was obtained with the imaging mode of the all-transmission imaging spectrograph on the Lick Observatory 3 m reflector. The scale of the 180 s exposure was $0''.73 \text{ pixel}^{-1}$, and the field of view was $\sim 1'$ in diameter. The stellar images were $\sim 1''.6$ FWHM on this image. The central part of this image is shown in Figure 2 as a contour plot. Measuring the FWHM of the west and east lobes, and correcting for the stellar FWHM by quadratures, the north-south sizes of the two lobes are $1''.87 \pm 0''.19$ (west lobe) and $1''.80 \pm 0''.60$ (east lobe). The east-west size of the brighter west lobe is $1''.03 \pm 0''.25$. The east lobe is so faint that its north-south size has a large uncertainty, and measurement of its east-west dimension is further complicated by blending with the west lobe. Hence no determination of the latter was possible. However, the two lobes are consistent with being identical in size and shape, but of different brightnesses. The measured separation (peak to peak) of the two lobes is $6''.4$.

3. RESULTS

In Table 3 the line ratios measured in § 2 are compared with published observations of HH objects. Several points must be noted before comparing the sets of objects. First, reddening is

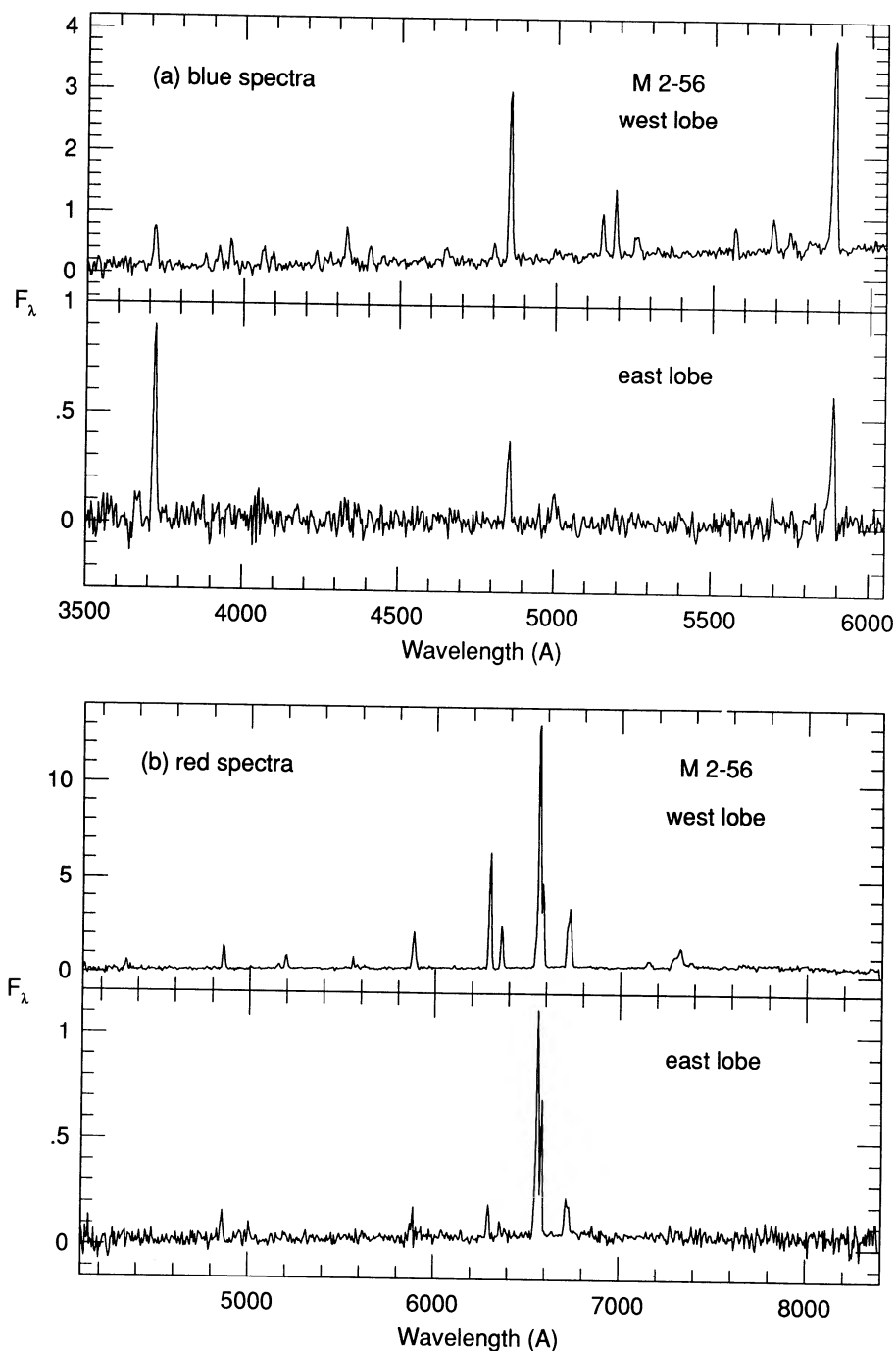


FIG. 1.—Low-resolution spectra of M2-56: (a) blue spectra; (b) red spectra. The vertical scales are in units of 10^{-16} ergs cm^{-2} $\text{\AA}^{-1}$. Note the strength of the low-ionization lines, such as [N I] $\lambda\lambda 5200$, [O I] $\lambda\lambda 6300$, 6363, [N II] $\lambda\lambda 6548$, 6583, and [S II] $\lambda\lambda 6716$, 6731 in M2-56W, the brighter of the two lobes. Such strong lines are indicative of shock heating. The line [O II] $\lambda 3727$ in M2-56E was unfortunately affected by an ion hit on the detector and hence is probably not really as strong as is indicated. While the spectrum of M2-56E is much weaker, it appears to have relatively weaker lines of [O I], [N I], [S II], and [Fe II]. There may be a hint of [O III] $\lambda 5007$ in M2-56E, which would indicate that it has a higher excitation spectrum than M2-56W.

both significant and problematic. A related problem is that the Balmer decrement, $H\alpha/H\beta$, is altered in shocks by collisional effects. The Balmer decrement is the most usual way of deriving extinction corrections for emission-line spectra, but this fails if the intrinsic Balmer decrement is considered unknown. The line ratios of HH objects presented in Dopita (1978) were corrected for reddening using the ratio of the [S II] transauroral

($\lambda\lambda 10318$, 10336) and auroral ($\lambda\lambda 4068$, 4076) lines as described by Miller (1968). The derived intrinsic Balmer decrements presented by Dopita vary between the case B value near 2.85 and values as high as 7.2 for HH 43S. Even with this dereddening procedure, however, the presence of inhomogeneously mixed dust can lead to problems, as can differing extinction laws. In any case, observations of the transauroral [S II] lines in GL

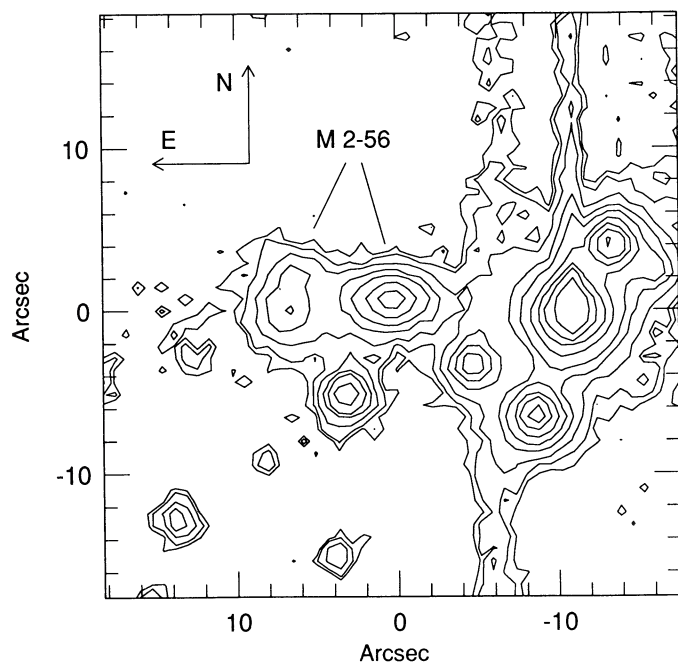


FIG. 2.—Contour plot of the area around M2-56 from a 3 minute red exposure. North is up, and east is to the left. Centered near (0, 0) is M2-56W, the brighter of the two lobes. The vertical streaks near $-6''$ and $-11''$ are charge bleeding from saturated stars on the exposure.

618 and M2-56 are not available, and the $[S\ II]$ reddening method cannot be used. For the purposes of easily comparing the line ratios of both shock models and HH observations with the spectra of GL 618 and M2-56, I adopt a somewhat different

approach. I assume an intrinsic Balmer decrement of 3.0 and use the standard extinction law as parameterized by Miller & Mathews (1972). While very simplistic in nature, and perhaps obscuring real variations in extinction laws and collisional effects, this has the distinct advantage of making the comparisons much more straightforward. The assumption will cause a problem in the search for spectral matches only if the change in shock Balmer decrement masks other significant effects, but, from the shock models presented in Table 3 and discussed below, this does not seem to be the case. Let me emphasize that this does *not* provide an accurate reddening estimate—it is only an expediency used for easy comparison.

Using this “dereddening” technique, and normalizing all corrected line fluxes to $H\beta = 100$, we compare our two proto-planetary to observations of HH objects in Table 3. Also included for comparison in Table 3 are several theoretical shock models; these will be discussed later. The theoretical models are generally parameterized by the preshock density, the abundances in the gas, and the preionization of the gas.

I should note here an additional complication which arises at least in the case of GL 618. Spectropolarimetry by Schmidt & Cohen (1981) demonstrated that the continuum polarization of GL 618 was quite high (26%), the forbidden-line polarizations were much lower (3.3%), and the permitted-line polarizations were intermediate (13%). The obvious conclusion from this is that in GL 618 the continuum and some of the permitted lines are reflected from either the central star or some deeper part of the nebula, while most of the forbidden-line radiation and the remainder of the permitted lines are formed in the shock. The presence of a radio-bright core in GL 618 (Kwok & Bignell 1984) probably indicates the presence of an ionization front deep in the optical nebulosity, and permitted-line radiation from this region may be reflecting off the dust associated

TABLE 3
COMPARISON OF LINE SPECTRA WITH HH OBJECTS^a AND SHOCK MODELS

Object	$\lambda 3727$	$\lambda 4861$	$\lambda 5007$	$\lambda 5159$	$\lambda 5200$	$\lambda 6300$	$\lambda 6563$	$\lambda 6584$	$\lambda 6725$
M2-56W	84	100	<0.06	18	139	169	300	96	104
GL 618E ^b	...	100	...	12	120	265	300	69	156
GL 618W ^b	...	100	...	14	114	378	300	96	173
HH 43N	...	100	15	6	38	116	300	89	242
HH 43C	...	100	0	5	101	216	300	77	456
HH 43S	...	100	0	15	128	219	300	57	484
HH 46S	...	100	9	23	24	177	300	85	186
HH 101	...	100	36	14	19	122	300	110	149
HH 101N	...	100	15	11	9	85	300	130	204
HH 24A	109	100	23	16	30	131	300	95	235
HH 40	198	100	62	17	26	102	300	128	234
HH 7	107	100	0	19	182	350	300	14	1094
HH 11	151	100	0	26	131	275	300	0	727
HRH: D20°	64	100	0	...	601	715	300	3	819
HRH: D40°	57	100	0	...	32	125	300	43	109
HRH: D60°	51	100	0	...	3	50	300	40	23
HRH: D80°	44	100	0	...	1	25	300	38	9
HRH: D100°	131	100	221	...	3	61	300	81	29
SM: A40 ^d	114	100	0	...	245	173	300	6	366
SM: B60 ^d	170	100	0	...	82	63	300	29	171
SM: C80 ^d	336	100	5	...	33	27	300	80	130
SM: E100 ^d	715	100	373	...	80	106	300	220	394

^a HH object measurements from Dopita 1978.

^b GL 618 measurements from Schmidt & Cohen 1981.

^c Hartigan, Raymond, & Hartmann 1987.

^d Shull & McKee 1979.

with the shock-heated optical lobes. The spectropolarimetry of Schmidt & Cohen (1981) is not of sufficient quality to determine an accurate set of line fluxes for *just* the intrinsic shock spectrum, although recent improved spectropolarimetry by Trammell, Dinerstein, & Goodrich (1991) confirms that different emission lines can show radically different polarizations, and may solve this problem. The lack of radio emission from M2-56 indicates that reflected light may not be a problem in this object. For the remainder of this paper we ignore this complication, keeping it in mind, however, as a source of uncertainty in the comparisons.

In Table 3 we can see that the line spectrum of M2-56W matches that of HH 46S quite well. Similarly, GL 618E has a spectrum similar to HH 43C, HH 43S, and HH 11. The spectrum of GL 618W is not matched particularly well by any of the HH object observations, but since it is even *more* extreme than GL 618E in the properties that signify low-velocity shocks (i.e., strong low-ionization lines), it seems reasonable that some combination of shock parameters would reproduce its spectrum. Alternatively, the removal of the reflected components of the emission lines, which would be possible with accurate spectropolarimetry, might make the GL 618W spectrum easier to match.

One obvious discrepancy in *all* of the proto-planetary nebula spectra is the weakness of the [S II] $\lambda\lambda 6717, 6731$ lines relative to the HH objects. The high-resolution spectrum of M2-56W includes the [S II] lines, and indicates an electron density of $1300^{+500}_{-350} \text{ cm}^{-3}$. This value is near the critical density for the 6716 Å line but not as high as the critical density of the 6731 Å line, and hence it seems unlikely that the [S II] lines can be collisionally quenched by a large factor in M2-56. In M2-56E the density is even lower, $150^{+150}_{-110} \text{ cm}^{-3}$. The density derived from the [S II] lines in GL 618 is $20,000 \text{ cm}^{-3}$ according to Schmidt & Cohen (1981), or $60,000 \text{ cm}^{-3}$ according to Westbrook et al. (1975), both near the high-density limit at which the [S II] ratio becomes insensitive. These authors also note that the strength of the [N I] 5200 Å emission indicates the presence of lower density gas, since the latter line has a critical density of 2000 cm^{-3} ; hence there is a superposition of material at different densities in GL 618.

Another interesting possibility is that the [S II] lines are affected by the molecular sulfur chemistry of the lobes. The bipolar proto-PN OH 0739-14 has been called the "Rotten Egg" nebula because of the apparently great abundance of sulfur molecules such as SO, SO₂, H₂S, OCS, and CS (Ukita & Morris 1983; Guilloteau et al. 1986; Morris et al. 1987). Perhaps the molecular chemistry has depleted the lobes of atomic sulfur, hence decreasing the strength of the [S II] $\lambda\lambda 6716, 6731$ lines. It seems unlikely, however, that much of this molecular gas will survive the shock.

Included in Table 3 are several shock models, five from Hartigan, Raymond, & Hartmann (1987, hereafter HRH87), labeled HRH, and four from Shull & McKee (1979, hereafter SM79), labeled SM. I have discussed the actual observations of shock-heated HH objects first, since, as will become clear, there are still significant differences among published shock models which have similar initial conditions. However, the shock models are still useful in estimating the shock conditions within the bipolar planetaries. In Table 3 the shock models have been given designations matching those within the original papers, except that the shock velocities (in km s^{-1}) have been appended to the letter codes from SM79. The models from HRH87 are their "equilibrium ionization" models rather

than their models which use complete preionization of the preshock gas. This is an important point for the low-velocity shocks under consideration. The preshock density of the HRH87 models is 1000 cm^{-3} , while the preshock density of the SM79 models is 10 cm^{-3} . From models with different densities published in both papers, it is clear that at higher densities there are significant effects on lines which have low critical densities, such as [O II] $\lambda 3727$ and [N I] $\lambda 5200$, but it is also clear that this is not the only source of discrepancy between the two sets of models. The present paper will not discuss in detail the effects of different shock parameters in these models, but will simply point out the two sets of models in Table 3 as typical of the range of line ratios which might be expected.

Both sets of shock models indicate that between shock velocities, v_s , of 80 and 100 km s^{-1} the [O III] $\lambda\lambda 4959, 5007$ emission lines become quite strong. For GL 618 and M2-56 the lack of significant [O III] emission indicates that $v_s < 100 \text{ km s}^{-1}$. Strong [N I] $\lambda 5200$ and [S II] $\lambda\lambda 6716, 6731$ occur at very low shock velocities in the HRH87 models, but are rather stronger in the SM79 models. Even in the latter models, however, shock velocities below 60 km s^{-1} are apparently required. Finally, in the models the [N II] $\lambda\lambda 6548, 6583$ lines are stronger for higher velocity shocks, close to $80\text{--}100 \text{ km s}^{-1}$. Such behavior would indicate a range in effective shock velocities between 20 and 80 km s^{-1} . This behavior is also seen in HH objects, where it is interpreted as indicating a bow shock. In a bow shock the gas velocity at the tip of the shock is normal to the shock itself, and hence the effective shock velocity is a maximum. On the sides of the bow shock, however, the shock is oblique and the effective velocity less. Geometric effects like these probably explain some of the line ratios seen in GL 618 and M2-56 as well.

Abundances will also affect the line ratios. Because accurate shock modeling is not easy to carry out—depending as it does on poorly determined geometries, preshock conditions, etc.—it is very difficult to derive accurate abundances from these spectra. However, it appears from a comparison between GL 618 and M2-56 and the HH objects listed in Table 3 that there is little reason to suspect major abundance anomalies between the protoplanetaries and the HH objects. The sole exception is [S II], which, as mentioned above, is consistently lower in the protoplanetaries than in the HH objects. Since it is important to know whether the proton-PNs are C-rich or O-rich, it would be interesting to compare the relative strength of the [C I] $\lambda 9849$ emission lines in GL 618 and M2-56 to a set of low-excitation HH objects.

The velocities observed directly in the lobes of these bipolar planetary nebulae (i.e., by means other than the shock spectra) are clearly of great importance. Gammie et al. (1989) and Genricharo et al. (1989) observed GL 618 in several molecular transitions in the radio and discovered a high-velocity molecular outflow with $v \sim 200 \text{ km s}^{-1}$. The latter authors in particular provide an extensive discussion of the outflow and its interpretation. High-resolution optical spectroscopy of GL 618 by Carsenty & Solf (1982) show an outflow velocity of $\sim 80 \text{ km s}^{-1}$. The high-resolution spectroscopy of M2-56 obtained in the present work indicates the presence of two kinematic components in the east lobe. Figure 3 shows the H α -[N II] region of the long-slit spectrum, and demonstrates that the blueshifted component is on the inside of the lobe (i.e., east, for the west lobe). The velocity difference between the two components is $\sim 110 \pm 20 \text{ km s}^{-1}$. If the redshifted component is a reflection of the inner blueshifted component, then this difference directly

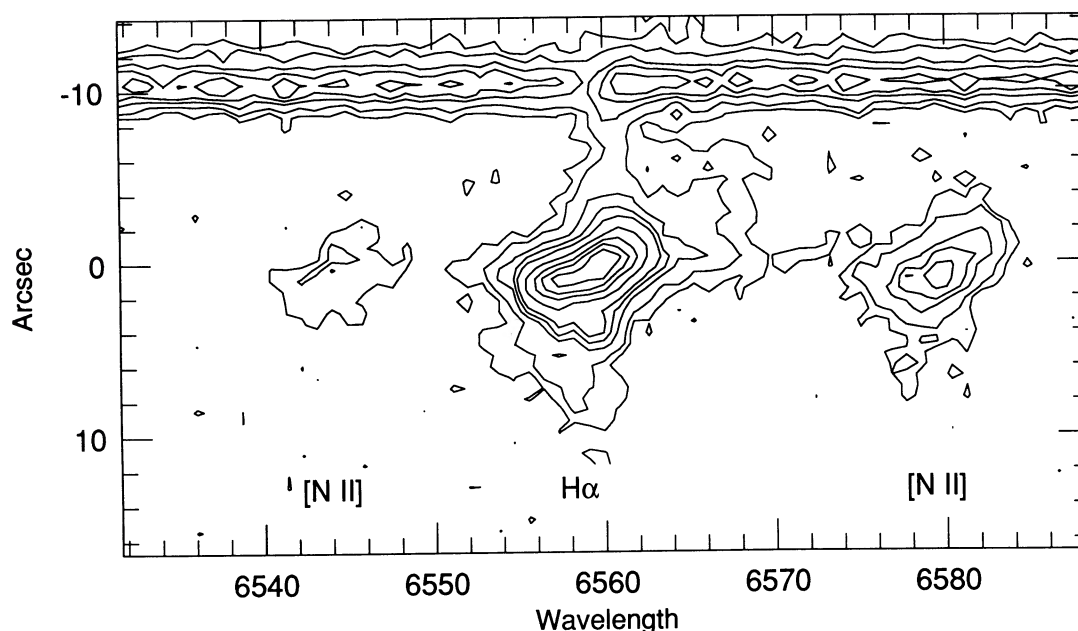


FIG. 3.—Contour plot of the long-slit high-resolution spectrum of M2-56. The dispersion is along the horizontal direction, with wavelength increasing toward the right, while the spatial direction is vertical and west is toward the top. Two distinct kinematic components of $H\alpha$ are visible in the west lobe, with the blueshifted component toward the inside of the lobe. This component appears to have an $[N II]/H\alpha$ ratio higher than the redshifted component, although the $[O I]/H\alpha$ ratio (not shown) appears to be the same in both. At the top is the continuum from the star just west of M2-56 (see Fig. 2).

measures the difference in the outflow velocities. If not, this value should be divided by $\sin i$, the effect of projection. These alternatives can be easily tested by high-resolution spectropolarimetry.

4. DISCUSSION

4.1. Shock Spectra

In § 3 it was shown that the optical spectra of GL 618 and M2-56 are consistent with low-velocity shocks, specifically with the shocks associated with HH objects. From shock models produced to explain HH objects it appears that M2-56 and GL 618 correspond to shock velocities in the range 20–60 km s^{-1} . On the other hand, the kinematics of the nebulae derived from other sources is typically $\sim 100\text{--}200 \text{ km s}^{-1}$. This behavior of a mean shock velocity which is lower than observed outflow velocities is typical of HH objects and bow shocks in general. In M2-56 the most blueshifted gas is found on the *inside* of the lobe, which is opposite to what would be expected if the elongated shape of the nebula were provided by a latitude-dependent outflow velocity. In such a case the outer, axial parts of the nebula would be expected to be expanding at the highest velocity. An interesting possibility is that a second, faster wind has turned on in the center of the nebula and is shocking against the first, slower wind. In this case we would expect different line ratios for the two kinematic components. This is difficult to assess accurately, since neither the spatial nor the kinematic resolutions of the components are great, but from Figure 3 it appears that the $[N II] \lambda 6584/H\alpha$ ratio is higher in the blueshifted inner component, although the $[O I] \lambda 6300/H\alpha$ ratio appears to be the same in both components. Table 3 shows that this is consistent with the shock models; $[N II] \lambda 6584/H\alpha$ increases nearly monotonically with v_s , while $[O I] \lambda 6300/H\alpha$ shows a minimum at shock velocities near 80 km s^{-1} . Carsenty & Solf (1982) found two $H\alpha$ components in

GL 618, again with the blueshifted component having a higher value of $[N II] \lambda 6584/H\alpha$. In the case of GL 618, however, the blueshifted component is *outside* of the redshifted component, which can be interpreted as a redshifted reflection of the inner core, plus a blueshifted shocked component.

The identification of the energy source for the gas as shock excitation has nonnegligible consequences for the determination of the physical parameters in these nebulae. For example, in § 3 it was noted that the excellent agreement between line ratios in HH objects and GL 618 implied near-solar abundances in the latter. This differs from the conclusions of Calvet & Peimbert (1983), who found a high N/O abundance in GL 618 of 5–10 times that of the Orion Nebula. This was then used to argue that GL 618 is likely to have had a massive progenitor star ($\geq 2.4 M_\odot$). The difference lies in their assumption that the nebula is photoionized. Gas which is photoionized can usually be well characterized by a single electron temperature, while shock excitation provides a wide range of temperatures and ionization levels as the gas is heated in the shock and then recombines in the “cooling tail.” This is the reason that the current work has not used the standard techniques employed on photoionized nebulae to determine the electron temperature of the emission-line gas. The derived temperature would depend mostly on the lines used for the determination, and in what region of the cooling tail the appropriate ions are most abundant.

4.2. Distances and Luminosities

The distances, D , and total luminosities, L , of GL 618 and M2-56 are also of interest. Previous estimates of D for GL 618 concentrate near 1.8 kpc (e.g., Schmidt & Cohen 1981), but these often are based on the assumption of photoionization. Another technique which can be used is the kinematic distance, in which the radial velocity, v_r , is used with a model of the

Galactic rotation curve to estimate D . For a simple rotation law,

$$v_r = AD \sin 2l \cos^2 b,$$

where $A = 15 \text{ km s}^{-1} \text{ kpc}^{-1}$. For GL 618, $(l, b) = (166^\circ 4, -6^\circ 5)$ and $v_r = -21.1 \text{ km s}^{-1}$ (Cernicharo et al. 1989), yielding $D = 3.1 \text{ kpc}$. For M2-56W, $(l, b) = (118^\circ 4, 8^\circ 4)$ and $v_r = -64 \text{ km s}^{-1}$ (from Fig. 3), hence $D = 5.2 \text{ kpc}$.

A second technique is the luminosity distance, in which the total observed flux is compared with an assumed or calculated total luminosity. In dust-enshrouded objects such as GL 618 and M2-56, almost the entire luminosity comes out in the *IRAS* infrared bands. Integrating the observed *IRAS* fluxes using a simple trapezoidal rule yields

$$L(\text{GL 618}) = 1.22 \times 10^4 L_\odot \left(\frac{D}{\text{kpc}} \right)^2,$$

and

$$L(\text{M2-56}) = 1.07 \times 10^3 L_\odot \left(\frac{D}{\text{kpc}} \right)^2.$$

The range of L predicted by evolutionary models of young PNs (the "Harmon-Seaton" evolutionary tracks) is $3.5 \leq \log_{10} (L/L_\odot) \leq 4.5$ (e.g., Shaw 1989). For three values of assumed luminosity Table 4 presents the derived distances, D , and height above the Galactic plane, $|z|$, of GL 618 and M2-56. The $|z|$ -heights should be compared with the scale height of PNs of $\sim 120 \text{ pc}$ (Aller 1973). Bipolar nebulae are often considered to have more massive progenitors, arguing for using a high value of L . On the other hand, the very rapid evolution of the most massive central stars implies short lifetimes and argues for observing lower values of L (Shaw 1989). Using $\log_{10} (L/L_\odot) = 4.0$ provides a reasonable compromise, and hence $D = 0.9 \text{ kpc}$ for GL 618 and $D = 3.1 \text{ kpc}$ for M2-56.

4.3. Evolutionary Status

The evolutionary predecessors to GL 618 and M2-56 are likely to be the OH/IR stars (e.g., Bowers & Knapp 1989). Most OH/IR stars are so deeply embedded in their dusty mass loss that they cannot be studied at optical wavelengths, but we do note in this context the evidence presented by Cohen (1980) and Cohen & Schmidt (1982) of shock excitation in the optical spectra of the carbon stars GL 1381, GL 1403, and GL 2699. These authors show that strong and variable [O I] $\lambda\lambda 6300, 6363$ and H α emission lines probably indicate shocks occurring as material from the episodic mass loss of the central star slams into the circumstellar shell. This activity in the carbon star envelopes directly foreshadows the similar activity in GL 618 and M2-56. However, GL 618 and M2-56 differ in showing relatively stronger and more continuous shock emission, pre-

sumably a result of a more stable outflow being driven by the hotter central stars. The hotter stars can more readily force a radiatively driven wind into the circumstellar material, while the very cool carbon stars appear to be losing mass via stellar pulsations, or possibly convective overshoot followed by radiative pressure.

Many other bipolar planetaries are known to have high outflow velocities (e.g., Paper I), and it seems likely that GL 618 and M2-56 will develop into planetaries like these. The evolutionary status of GL 618 and M2-56 must be between the OH/IR stars and photoionized young planetaries like M4-18 and BD + 30°3639. GL 618 shows significant radio flux, which is increasing with time (Kwok & Feldman 1981) and is confined to a region smaller than the optically visible lobes. This is undoubtedly an expanding ionization front which represents the transition of this object from a shock-heated proto-planetary nebula to a fully ionized planetary nebula. Gottlieb & Liller (1976) have also found that the optical brightness of GL 618 increased between the years 1940 and 1975. They used blue photographic magnitudes from Harvard plates. This optical brightening may represent an increase in the reflected contribution from the ionized region, in which case spectropolarimetry at the current epoch should show higher polarization for the Balmer lines. Or it may represent an increase in the surface area of the shock interaction. It might also represent the time development of the shock, which would predict that the lower ionization lines should be more intense now, as the cooling tail of the shock has developed more fully. Last, an increase in the preshock density could explain an intensity increase, as $I \propto N_e^2$. This would predict that the high-ionization lines would be more intense now, since the cooling tail has not had time to respond to the higher densities encountered.

M2-56 has little or no radio flux and hence may correspond to an earlier evolutionary stage. However, the distinct kinematic components seen in high-resolution spectra could indicate that a second, higher velocity wind source has already turned on in this object. It is conceivable, of course, that the onset of photoionization and the beginnings of a second wind stage might not occur in the same evolutionary order in stars of different central star masses.

The rarity of the transition stage represented by GL 618 and M2-56 argues for a very short lifetime. The optically faint low-excitation object GL 2088 apparently has a high [N I] $\lambda 5200/\text{H}\beta$ ratio (Cohen & Kuhl 1977), but has not been well studied. The peculiar object M3-60 (de Muizon et al. 1988; Becker & Fesen 1988) may be another example, but with a more nearly spherical geometry. However, the nature of M3-60 is still being debated. The presence of shock emission in GL 618 and M2-56 gives us a unique opportunity to probe directly the kinematics of the AGB-PN transition.

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TABLE 4
DISTANCES AND $|z|$ -HEIGHTS

$\log_{10} (L/L_\odot)$	GL 618		M2-56	
	D (kpc)	$ z $ (pc)	D (kpc)	$ z $ (pc)
3.5.....	0.51	58	1.72	251
4.0.....	0.91	103	3.06	447
4.5.....	1.61	182	5.44	795

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