THE ASTROPHYSICAL JOURNAL, 267:179–183, 1983 April 1

THE NATURE OF NML CYGNUS

M. MORRIS[1,2] AND M. JURA[1]
Received 1982 July 12; accepted 1982 September 24

ABSTRACT

We suggest that the H II region observed near NML Cygnus, a highly evolved mass-losing giant, results from the photoionization of the outflow by the luminous, hot stars in the Cyg OB2 association. NML Cyg is at a projected distance of 100 pc from Cyg OB2, but because all of these objects are near the center of the X-ray emitting superbubble in Cygnus where the hydrogen is mostly ionized, the Lyman continuum photons probably can travel this far without appreciable absorption. The observed structure of the H II region matches this hypothesis quite well.

This picture provides the first reasonably precise estimate of the distance to NML Cyg: 2 kpc. At this distance, the star has a luminosity of 5×10^5 $L_\odot$ and a minimum mass loss rate of 6.4×10^{-5} $M_\odot$ yr^{-1}. We conclude that NML Cyg is a massive (50 $M_\odot$) star in a highly evolved state. It is likely that it will soon become a supernova and contribute to the general expansion of the superbubble. Before doing so, however, it may endure a phase as a W-R star. If it remains a mass-losing supergiant when it does explode, there may be enough dust around it that it would be optically inconspicuous even if interstellar extinction were negligible. The possibility that infrared supernovae are common would be very important for understanding the rate of stellar explosions, the formation of pulsars, and nucleosynthesis in the Galaxy.

Subject headings: nebulae: H II regions — nebulae: individual — stars: supernovae

I. INTRODUCTION

Ever since NML Cyg was discovered (Neugebauer, Martz and Leighton 1965), its nature has been uncertain because its distance and luminosity are not known. It is clear that it is a dust-shrouded late type star having a large infrared excess (Herbig and Zappala 1970; Gehrz and Woolf 1971; Hyland *et al.* 1972), and it is probably losing mass rapidly (see Zuckerman 1980 for a review of such stars). Observations of powerful H_2O, OH, and SiO masers have led to the classification of NML Cygnus as a supergiant OH/IR star (Bowers 1981), but because it is apparently not variable (Hyland *et al.* 1972), it is probably not a typical OH/IR star. Maser emission from OH has been detected as far as 2″ from the star itself, supporting the idea that we are witnessing an outflow from the star (Mashedar, Booth, and Davies 1974; Moran *et al.* 1977).

NML Cyg is partially surrounded by an H II region which is heavily obscured by intervening interstellar matter (Rubin, Ford, and Christy 1967). This H II region has recently been mapped in the continuum at 21 cm at Westerbork (Habing, Goss, and Winnberg 1982), and it seems clearly associated with the star. Here we propose that the H II region has been created by ionizing radiation from the Cyg OB2 association. The idea that NML Cyg might lie at the distance of the Cyg OB2 association was previously examined by Johnson (1967) and Herbig and Zappala (1970), although because of their different luminosity classifications, their conclusions differed. The close agreement between the observed structure of the H II region and that predicted by our model provides strong evidence that NML Cyg is indeed at the distance of the association, 2 kpc. At this distance, it is among the most luminous red stars known (see, for example, Humphreys 1980).

[1] Department of Astronomy, UCLA.
[2] Department of Astronomy, Columbia University.

II. PHOTOIONIZATION OF CIRCUMSTELLAR OUTFLOWS

Recently, there have been discussions of the photochemistry in the outflows of late-type stars immersed within H I regions (Jura and Morris 1981; Huggins and Glassgold 1982; Glassgold and Huggins 1982; Morris and Jura 1983). Here, we discuss the ionization structure of an initially neutral outflow immersed within an H II region.

The calculations employ simplifying assumptions whose validity is supported by our numerical analysis. First, the mass loss is assumed to occur at a constant rate ($\dot{N}$ in units of H atoms s^{-1}) and to be spherically symmetric with a constant outflow velocity, $v = 23$ km s^{-1} (Bowers, Johnston, and Spencer 1981). Therefore we are implicitly assuming that the density varies as r^{-2} and that photoionization of the gas and the resulting heating do not affect the outflow speed appreciably because the gas is highly supersonic both at the outset and after it is ionized. Second, dust opacity is ignored; it is probably negligible at radii beyond the inner radius of the ionized gas around NML Cyg, 10^{18} cm. Finally, we assume "on-the-spot" balance between photoionization and recombination. With these assumptions our model is similar to the "inverse Strömgren spheres" computed by Icke, Gatley, and Israel (1980).

While most of the hydrogen is probably ejected in molecular form, we neglect this complication and assume that all the gas in the ionized zone enters as atoms. This approximation is valid if the H_2 dissociation front is closer to the mass-losing star than the ionization front. In order to examine this requirement quantitatively, one must compare the relative numbers of dissociating and ionizing photons reaching the ionization surface.

The number of recombinations and reionizations endured by each hydrogen atom after it streams through the ionization surface at $\beta = 0$, defined below, is

$$\zeta = \int_{r_0}^{\infty} \frac{\alpha n_e(r) dr}{v} = \frac{\alpha n_e(r_0) r_0}{v} , \qquad (1)$$

where r_0 is the radius of the ionization surface at $\beta = 0$, and $\alpha = 3 \times 10^{-13}$ cm^3 s^{-1} is the recombination rate. For NML Cyg at a distance of 2 kpc (see below), the observations of Habing, Goss, and Winnberg (1982) give $r_0 = 10^{18}$ cm and $n_e(r_0) = 85$ cm^{-3}. Therefore, $\zeta = 11$, which means that only one-eleventh of all incident Lyman continuum photons reach the ionization surface to ionize the fresh neutral material arriving there. On the other hand, almost all photons which can dissociate H_2—those in the Lyman and Werner bands between 912 and 1100 Å—reach the ionization surface. However, only about one-ninth of all the photons absorbed in these bands actually leads to dissociation.

As a result of these considerations, we find that the condition that the dissociation front occur closer to the star than the ionization front is simply that the number of dissociating photons emitted by the UV source be roughly equal to or greater than the number of Lyman continuum photons. If the Cyg OB2 association contains several B supergiants, this condition is likely to be met. More sophisticated treatments of the relative amounts of atomic and molecular hydrogen are possible (Black 1978; Hill and Hollenbach 1978; London 1978).

The source of ionizing photons is assumed to be compact and distant, and therefore the illumination of the envelope is taken to be plane-parallel along the axis joining the star and the source of illumination, the z-axis in Figure 1. We compute the boundary of the ionized gas in terms of the radial distance to the boundary, r, as a function of the angle β, where β is measured from the z-axis.

The relation between r and β is given by the following equation which balances the incident ionizing flux, I, in units of photons cm^{-2} s^{-1} against recombinations plus a source term:

$$\begin{aligned} I &= \int_0^{\infty} \alpha n_e^2 dz + \dot{N} \sin \phi / 4\pi r^2 \\ &= \alpha(\dot{N}/4\pi v)^2 \int_0^{\infty} (r^2 + z^2 + 2rz \cos \beta)^{-2} dz \\ &\quad + \dot{N} \sin \phi / 4\pi r^2 , \end{aligned} \qquad (2)$$

where ϕ is the angle between the radius vector and the tangent to the ionization surface at the point of interest.

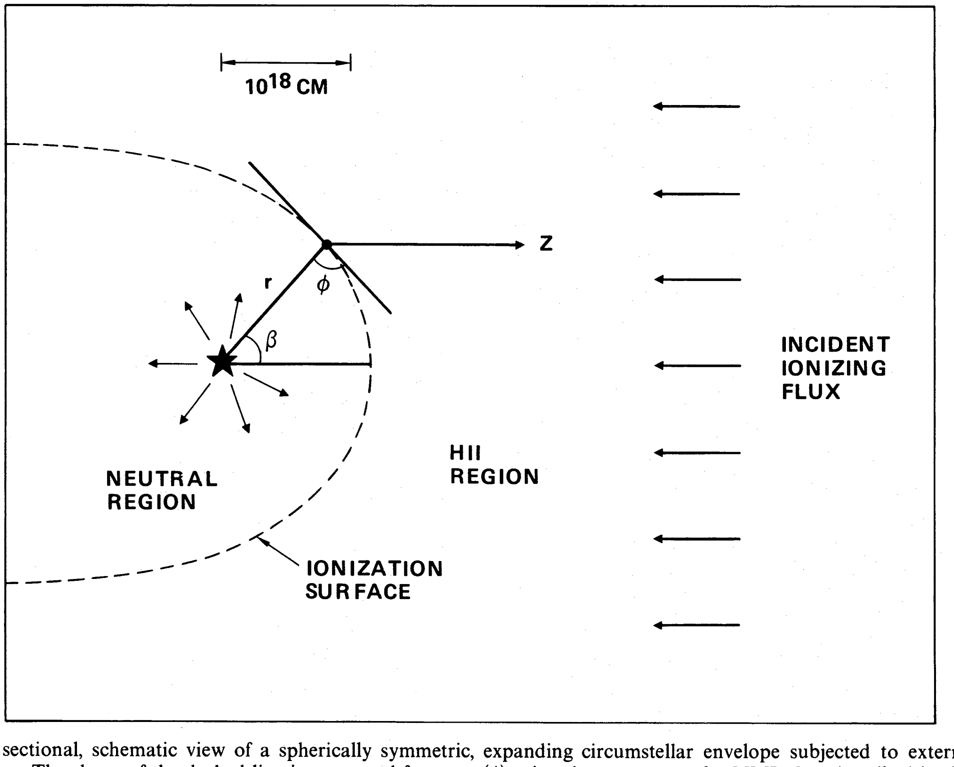

FIG. 1.—Cross sectional, schematic view of a spherically symmetric, expanding circumstellar envelope subjected to external plane-parallel ionizing illumination. The shape of the dashed line is computed from eq. (4) using the parameters for NML Cyg described in the text.

Solving the integral in equation (2) and noting after some algebra that

$$\sin \phi = (1 + \cot^2 \phi)^{-1/2} = [1 + (d \ln r/d\beta)^2]^{-1/2} , \quad (3)$$

we rewrite equation (3) as

$$I4\pi r^2/\dot{N} = \alpha\dot{N}(\beta/\sin \beta - \cos \beta)/(8\pi v^2 r \sin^2 \beta) + [1 + (d \ln r/d\beta)^2]^{-1/2} . \quad (4)$$

This equation can be solved numerically for r as a function of β using the boundary condition $d \ln r/d\beta = 0$ at $\beta = 0$. For NML Cyg, it gives the surface shown in Figure 1. The minimum distance of the ionization surface to the star can be approximated by ignoring the second term on the right-hand side of equation (4) and by setting $\beta = 0$. Thus

$$r_0 = [(\alpha/3I)(\dot{N}/4\pi v)^2]^{1/3} \quad (5)$$

In order to compare our model with the observations of Habing, Goss, and Winnberg (1982), we assume that NML Cyg and Cyg OB2 are both located in the plane of the sky at the same distance from the Earth. The maximum emission measure is then found at a projected distance r_0 from NML Cyg and is given by

$$\left(\int n_e^2 dL\right)_{\max} = \pi/(2r_0^3) \quad (\dot{N}/4\pi v)^2 = 3\pi I/2\alpha . \quad (6)$$

The angular separation between NML Cyg and Cyg OB2 star 5 = BD + 40°4220 = V729 Cyg, the most luminous star in the association, is 2°.91. For a distance to the association of 2000 pc (Abbott, Bieging, and Churchwell 1981; Cash *et al.* 1980), this implies a projected distance of 100 pc. If the Lyman continuum luminosity in the association is 5×10^{50} photons s^{-1} (Abbott, Bieging, and Churchwell 1981), this implies that at NML Cyg, $I = 4.2 \times 10^8$ photons cm^{-2} s^{-1}, and from equation (6) we expect that $(n_e^2 L)_{\max} = 2000$ cm^{-6} pc. This is in very good agreement with the observed value of 1500 cm^{-6} pc and lends considerable support to our model. In addition, the observed radio emission peaks to the west of NML Cyg, in a direction which corresponds well with the direction to Cyg OB2, (P.A. ~ 294°). Other OB associations—Cyg OB1, Cyg OB8, and Cyg OB9—are located to the west of NML Cyg in projection on the sky, but they can all be ruled out as the principal ionization source for the NML Cyg envelope because their Lyman continuum luminosities are far smaller than that of Cyg OB2.

The radial velocities of NML Cyg and Cyg OB2 stars are sufficiently close that our model is plausible. That is, if we adopt for the LSR velocity of NML Cyg the midpoint of the extremes of the OH maser velocities measured by Moran *et al.* (1977), $v_{\rm LSR} = -2$ km s^{-1}. For BD +40°4220 = Cyg OB2 star 5, Bohannan and Conti (1976) give $v_{\rm LSR} = -16 \pm 4$ km s^{-1}, and for Cyg OB2 star 12, Herbig and Zappala (1970) give $v_{\rm LSR} = +17 \pm 5$ km s^{-1}; the mean of these velocities is quite close to that of NML Cyg.

The maximum intensity in the radio contours of the H II region near NML Cyg is displaced about 35″ from the star (Habing, Goss, and Winnberg 1982). For a distance of 2000 pc, this implies that $r_0 = 1.0 \times 10^{18}$ cm. In constructing models to reproduce the observations in detail, one must account for the considerable beam averaging occurring over the 25″ × 39″ Westerbork beam. In doing so, we find using equation (6) that $I = 7.0 \times 10^8$ photons cm^{-2} s^{-1} is needed to match the observed beam-averaged emission measure of 1500 cm^{-6} pc. This value of I is 70% larger than would be derived from the estimate of the Lyman continuum luminosity given by Abbott *et al.* (1981) for Cyg OB2, but it is easily within the range of uncertainty of this quantity. If we adopt this value of I, then equation (4) implies that $\dot{N} = 2.5 \times 10^{45}$ s^{-1} or 6.4×10^{-5} $M_\odot$ yr^{-1}. Therefore, at $R = 1.0 \times 10^{18}$ cm, $n_e = 85$ cm^{-3} as noted above. Our derived mass loss rate should be regarded as a lower limit since some fraction of the material in the H II region may in fact remain molecular. This limit is consistent with the upper limit for emission in the $J = 1$–0 rotational transition of CO by Zuckerman *et al.* (1977), and the formula for mass loss employed by Knapp *et al.* (1982).

Using the inferred distribution of ionized gas, we display in Figure 2 our map for the radio continuum compared to the observations of Habing, Goss, and Winnberg (1982). It can be seen that we find reasonably good agreement with both the shape and orientation of their contours. Since the outermost radio contours extend as far as 100″ from the star, the minimum radial extent of the envelope is 1 pc, larger than the known extent of any other envelope. If the outflow velocity has been constant, our model implies that NML Cyg has been rapidly losing mass for 40,000 years, and that the total mass in the envelope is at least 2.5 $M_\odot$.

III. DISCUSSION

Our first conclusion is that NML Cygnus lies in the Cygnus superbubble at a distance of 2 kpc. According to the photometry of Hyland *et al.* (1972), this implies that the star has a luminosity of 5×10^5 $L_\odot$ ($M_{\rm bol} = -9.4$) and, as derived above, a mass loss rate of 6.4×10^{-5} $M_\odot$ yr^{-1}. This luminosity is also consistent with the interpretation of the OH maser observations by Bowers (1981).

Because of its high luminosity, NML Cygnus is probably a massive star of perhaps 50 $M_\odot$ (see Stothers and Chin 1974). The likely fate of a massive red supergiant is to become a supernova. In fact, there is now considerable evidence that the precursors to type II supernovae are red supergiants with preexplosion mass loss rates on the order of 10^{-5} $M_\odot$ yr^{-1} (Chevalier 1982). The Cygnus superbubble may have been produced either by a series of such explosions (Cash *et al.* 1980) or by stellar winds (Abbott, Bieging, and Churchwell 1981). Regardless, NML Cyg would contribute to the continued expansion in this region if it became a supernova.

Before becoming a supernova, NML Cyg might evolve toward the blue to become a WR star (Maeder 1981*a*, *b*). Indeed, Maeder argues that, for post–main-sequence

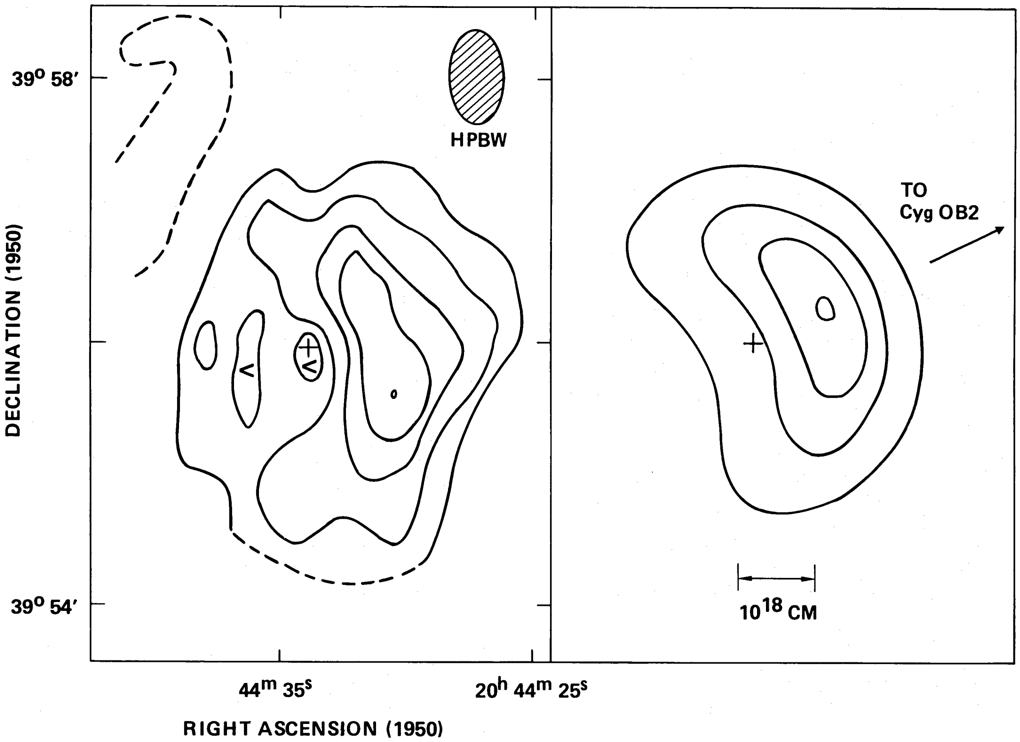

FIG. 2.—Comparison of theoretical and observed radio contours around NML Cyg; both are drawn to the same scale, assuming a distance of 2 kpc. The observed map is taken from Habing *et al.* 1982; their contour levels are 0.5, 1, 2, 3, and 4 mJy per beam, the peak corresponding to a beam-averaged emission measure of 1500 cm^{-6} pc. For the theoretical contours, we employ the parameters for the outflow described in the text which give best agreement with the observations. The calculated emission measures have been convolved with a 25″ by 39″ Gaussian beam in order to facilitate comparison with observations. The contour levels are chosen to correspond to the four highest contours on the observational map.

stars as luminous as NML Cyg, the total lifetime in the WR stage is comparable to, or greater than, the lifetime in the red supergiant stage. In this regard, our lower limit of 4×10^4 years on the duration of the present stage of mass loss is interesting and should be extended with more sensitive observations.

If NML Cyg does become a supernova, it may not be optically bright because there is so much dust around it. Falk and Scalo (1975) have considered this possibility for stars with circumstellar envelopes that extend out to 10 stellar radii, and they argued that dust attenuation is probably not important. However, since they published their work, it is clear that circumstellar envelopes are much more extended than previously believed, so that some dust may survive a supernova explosion.

If the dust-to-gas ratio around NML Cyg is similar to the value in the interstellar medium in the solar neighborhood, then the outward radial dust opacity in the visual can be expressed as $\tau_V = 5.7 \times 10^{-22}\ N(\mathrm{H})$ (see, for example, Jura and Morris 1981), where $N(\mathrm{H})$ is the radial column density of hydrogen nuclei outward from radius r. We may therefore write that

$$\tau_V = 5.7 \times 10^{-22} \dot{N}/(4\pi r v)\ .$$

With the parameters for NML Cyg described above, this gives

$$\tau_V = 0.5/r_{17}\ ,$$

where r_{17} is the radius in units of 10^{17} cm. According to Wright (1980), we might expect grains around a supernova to be evaporated by the light pulse out to a distance of 2×10^{17} cm. Specifically, we may write for the critical radius, r_{crit}, that

$$r_{\mathrm{crit}} = [L/(16\pi\sigma T_{\mathrm{crit}}^{\ 4})Q_V/Q_{\mathrm{IR}}]^{1/2}\ ,$$

where L is the luminosity of the supernova, T_{crit} the evaporation temperature, and Q_V/Q_{IR} the relative cross sections for absorption and emission. Wright (1980) uses $T_{\mathrm{crit}} = 1000$ K; Falk and Scalo (1975) suggest that T_{crit} may be as high as 1900 K. Therefore, r_{crit} could be appreciably smaller than the nominal value suggested by Wright (1980). For the NML Cyg H II region, Rubin, Ford, and Christy (1967) find that the intensity ratio of Hα/[N II]λ6583 Å is about unity, suggesting that the nitrogen abundance may be enhanced, as appears to be the case for the precursor to Cas A (Chevalier and Kirshner 1978). Indeed, the abundances in the circumstellar envelope around the mass-losing, oxygen-rich supergiant, α Ori, are very different from solar values, presumably because the observed material has been subject to substantial nuclear processing (Jura and Morris 1981). It is therefore quite possible that the dust-to-gas ratio around stars such as NML Cyg is appreciably higher than in the local interstellar medium. Consequently, even if interstellar extinction were unimportant, it is imaginable that when NML Cyg does become a supernova, it will be optically inconspicuous but bright in the infrared.

Chevalier (1981) has discussed the possibility that optically faint supernovae exist; here we suggest such objects might occur because of extinction produced by circumstellar dust. If large numbers of infrared supernovae occur, this would be most important for understanding nucleosynthesis and the formation rate of pulsars in the Galaxy.

This work has been partly supported by NASA.

REFERENCES

Abbott, D. C., Bieging, J. H., and Churchwell, E. 1981, *Ap. J.*, **250**, 645.
Black, J. H. 1978, *Ap. J.*, **222**, 125.
Bohannan, B., and Conti, P. 1976, *Ap. J.*, **204**, 797.
Bowers, P. F. 1981, *A.J.*, **86**, 1930.
Bowers, P. F., Johnston, K. J., and Spencer, J. H. 1981, *Nature*, **291**, 382.
Cash, W., Charles, P., Bowyer, S., Walter, R., Garmire, G., and Riegler, G. 1980, *Ap. J.* (*Letters*), **238**, L71.
Chevalier, R. 1981, *Fundamentals Cosmic Phys.*, **7**, 1.
———. 1982, *Ap. J.*, **259**, 302.
Chevalier, R., and Kirshner, R. P. 1978, *Ap. J.*, **219**, 931.
Falk, S. W., and Scalo, J. M. 1975, *Ap. J.*, **202**, 690.
Gehrz, R. D., and Woolf, N. J. 1971, *Ap. J.*, **165**, 285.
Glassgold, A. E., and Huggins, P. J. 1982, *Ap. J.*, submitted.
Habing, H. J., Goss, W. M., and Winnberg, A. 1982, *Astr. Ap.*, **108**, 412.
Herbig, G. H., and Zappala, R. R. 1970, *Ap. J.* (*Letters*), **162**, L15.
Hill, J. K., and Hollenbach, D. J. 1978, *Ap. J.*, **225**, 390.
Huggins, P. J., and Glassgold, A. E. 1982, *Ap. J.*, **252**, 201.
Humphreys, R. M. 1980, *Ap. J.*, **241**, 587.
Hyland, A. R., Becklin, E. E., Frogel, J. A., and Neugebauer, G. 1972, *Astr. Ap.*, **16**, 204.
Icke, V., Gatley, I., and Israel, F. 1980, *Ap. J.*, **236**, 808.
Johnson, H. L. 1967, *Ap. J.*, **149**, 345.
Jura, M., and Morris, M. 1981, *Ap. J.*, **251**, 181.
Knapp, G. R., Phillips, T. G., Leighton, R. B., Lo, K. Y., Wannier, P. G., Wooten, H. A., and Huggins, P. J. 1982, *Ap. J.*, **252**, 616.
London, R. 1978, *Ap. J.*, **225**, 405.
Maeder, A. 1981*a*, *Astr. Ap.*, **99**, 97.
———. 1981*b*, *Astr. Ap.*, **102**, 401.
Mashedar, M. R. W., Booth, R. S., and Davies, R. D. 1974, *M.N.R.A.S.*, **166**, 561.
Moran, J. M., Ball, J. A., Yen, J. L., Schwartz, P. R., Johnston, K., and Knowles, S. H. 1977, *Ap. J.*, **211**, 160.
Morris, M., and Jura, M. 1983, *Ap. J.*, **264**, 546.
Neugebauer, G., Martz, D. E., and Leighton, R. B. 1965, *Ap. J.*, **142**, 399.
Rubin, V. C., Ford, W. K., and Christy, J. W. 1967, in *IAU Symposium 30, Determination of Radial Velocities and Their Applications*, ed. A. H. Batten and J. F. Heard (London: Academic), p. 5.
Stothers, R., and Chin, C. 1979, *Ap. J.*, **233**, 267.
Wright, E. L. 1980, *Ap. J.* (*Letters*), **242**, L23.
Zuckerman, B. 1980, *Ann. Rev. Astr. Ap.*, **18**, 263.
Zuckerman, B., Palmer, P., Morris, M., Turner, B. E., Gilra, D. P., Bowers, P. F., and Gilmore, W. 1977, *Ap. J.* (*Letters*), **211**, L97.

M. Jura: Department of Astronomy, UCLA, Los Angeles, CA 90024

M. Morris: Department of Astronomy, Columbia University, New York, NY 10027