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A MODEL FOR THE COMETARY NEBULA NGC 2261*

THOMAS T. ARNY AND KENNETH P. BECHIS
Department of Physics and Astronomy, University of Massachusetts, Amherst
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ABSTRACT

It is suggested that the cometary nebula NGC 2261 associated with R Mon is produced by the interaction of a mass flow representing the expulsion of a circumstellar shell from the star with the interstellar matter through which the star is moving. A model based on the interaction of the ejected matter with the surrounding interstellar gas is used to calculate the shape of the nebula. The model is characterized by the mass-loss rate, velocity of outflow from the star, velocity of the star, and cloud density. The nebular size and shape are both found to be in good agreement with observations for reasonable values of the parameters governing the model.

Subject headings: interstellar: matter — nebulae: individual — stars: pre–main-sequence

I. INTRODUCTION

The star R Mon and its associated "cometary" nebula NGC 2261 have been the subject of many studies. Slipher (1912) showed that the nebula was illuminated by reflected light from R Mon. Early work by Joy (1945) and Greenstein (1948) drew attention to the spectral peculiarities of the star and nebula, while Hubble (1916) noted the variability of the nebulosity. Some 40 pictures drawn from the collection at Lowell Observatory have been published by Duncan (1956). These photographs show clearly the remarkable changes that occur in the illumination of the nebula on time scales of months. Figure 1 is a sketch of the system. Herbig (1960, 1968) has described the spectra of R Mon and has published some detailed photographs of it and the nebulosity; he concluded that the star itself is heavily obscured and has a nonstellar image. The star's spectrum is peculiar, roughly class Ae, and shows a mixture of absorption and emission features suggestive of a chromosphere surrounded by a cooler absorbing shell. The nebula has been studied recently by Stockton, Chesley, and Chesley (1975), who also obtained spectra of R Mon and measured radial velocities. They found that R Mon shows emission lines with a radial velocity of about 27 km s^{-1}, which they take as the velocity of the star. Emission lines in the nebulosity seem to show a roughly constant velocity of 58 km s^{-1} independent of position. However, the absorption lines show a radial velocity that drops off monotonically from -78 to -280 km s^{-1} as one moves away from R Mon along the fan. Stockton *et al.* interpret this variation as light from the expanding shell reflected off the dust in the nebula. In their model, the variation of the velocity along the nebula is a light-travel-time effect giving a record of the expansion velocity of the absorbing shell. One of the spectral peculiarities of NGC 2261 is the presence of O II emission lines seen not only in the nebula but also in the surrounding gas. This is surprising in view of the late spectral class of R Mon. Stockton *et al.* (and references therein) suggest that this can best be interpreted as due to ionizing radiation from S Mon approximately 1° northeast of R Mon. Thus R Mon may lie inside the H II region produced by S Mon.

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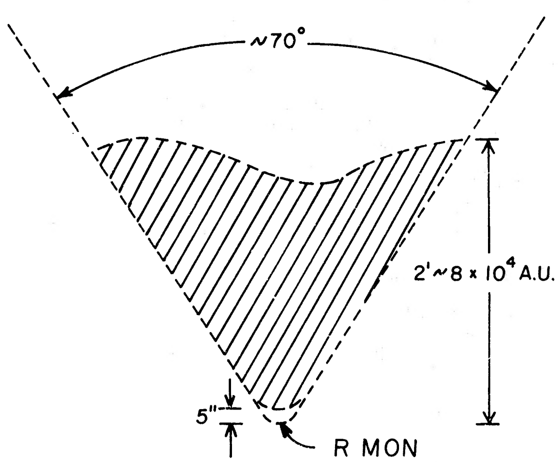

FIG. 1.—Sketch of nebula showing approximate scale. Distance is assumed to be 700 pc.

There have been several radio observations of R Mon. Wilson, Schwartz, and Epstein (1973) have observed R Mon in CO and find it to be distributed in a cloud approximately 2′ across, with a radial velocity of 10.5 km s^{-1} centered on the nebula. Loren, Vanden Bout, and Davis (1973) also report CO emission but find it strongly peaked on R Mon. Finally, R Mon is a powerful infrared source (Mendoza 1966), suggesting that it is surrounded by a large dust shell.

With these observations in mind, a simple model can be constructed which offers an explanation for several features of this peculiar object. It is proposed that R Mon is an A emission-line shell star ejecting its shell and moving through the H II region produced by S Mon. Matter, as it streams out of the star's atmosphere, slowly accelerates the shell into the surrounding gas. The latter pushes on the shell and sweeps it back to form a fan-shaped wake. The CO emission arises in the shell and in the material swept into the wake. In what follows, we will show how this model can explain rather naturally the basic features of the object. We will begin by considering the region immediately surrounding R Mon and then will turn to the interaction of a shell from a moving star expanding into a low-density medium.

II. ENVIRONMENT OF R MONOCEROTIS

CO observations show that the region of Monoceros is an active site of star formation. The projected position of R Mon lies nearly midway between the two extremely young clusters NGC 2264 and NGC 2244. The former is dominated by the O7 star S Mon, which produces an H II region whose nebulosity can be traced outward several degrees and past R Mon. Radio continuum observations show only extremely weak emission at the position of R Mon, suggesting that the electron density in that direction is low. This is consistent with the apparent faintness of the nebulosity. More important, it is confirmed by an estimate of the radius of the Strömgren sphere produced by S Mon. If indeed UV radiation from S Mon is responsible for the weak O II emission at R Mon, as suggested by Stockton *et al.*, then an upper limit can be set on the intervening electron density, n_e, of $n_e \lesssim 15\ \text{cm}^{-3}$. This is consistent with both weak emission nebulosity, the O II line ratios, and the radio continuum measurements referred to earlier. The CO observations show that, while R Mon and perhaps NGC 2261 are CO sources, the surrounding area is not, consistent with the low density and ionization indicated by radio continuum and optical observations. There is also no H I that can be unambiguously associated with the immediate surroundings of R Mon. We will therefore assume that R Mon is located in a diffuse H II region with $n_e \leq 15\ \text{cm}^{-3}$.

III. MODEL OF A CONICAL NEBULA

The motion of an object with a deformable boundary through a resisting medium has received considerable attention because of its bearing on the shape of the bow shock surrounding the Earth and on the confinement of extended radio sources. In the case of the Earth's magnetosphere, this process has been modeled by Mead and Beard (1964) using the simple procedure of balancing the momentum flux at the surface due to the streaming of the surrounding matter against the gas pressure produced in the object itself. A variety of similar models worked out by various authors are described by Pacholczyk (1977), while Weaver *et al.* (1977) make a similar analysis for mass loss from O stars. For a loss at rate $\dot{M}$, we must balance the dynamic pressure from the mass loss ($\rho_i v_i^2$) against the streaming pressure from the medium ($\rho_0 v_0^2$), where ρ and v are the density and velocity in the flow and the subscripts i and 0 indicate matter from the shell and cloud, respectively. We will choose a coordinate system centered on the star with the x-axis in the direction of the star's motion (Fig. 2). We assume that the flow from the star terminates at a thin shell on whose outer surface the interstellar matter impinges. Since for spherically symmetric mass loss, $4\rho\pi r^2 v_i = \dot{M}$, the internal pressure is just $\rho_i v_i^2 = \dot{M} v_i/(4\pi r^2)$. Equating this to the external pressure $\rho_0 v_0^2$, we find that the shell formed by the interaction of the two flows on the upstream side of the star crosses the x-axis at a distance

$$r = (\dot{M} v_i / 4\pi\rho_0 v_0^2)^{1/2} \equiv \beta\ . \tag{1}$$

While we have ignored the asymmetry that the streaming motion will produce, this result should give a close approximation to the flow immediately in front of the star. Eliminating ρ_0 in terms of the H II density n_0 and the molecular weight μ and assuming that the ejected material moves at a constant velocity, we obtain $r = 3 \times 10^8 (\dot{M} v_i / \mu n_0 v_0^2)^{1/2}$ AU, where $\dot{M}$ is measured in $M_\odot\ \text{yr}^{-1}$, v_i and v_0 are in km s^{-1}, and n_0 is in particles cm^{-3}. Kuhi (1964) has shown that, for a typical T Tauri star, $\dot{M} = 4 \times 10^{-8}\ M_\odot\ \text{yr}^{-1}$ and $v_i = 200\ \text{km s}^{-1}$. Because it is not known whether the star's radial velocity is given by the emission or absorption lines, or by neither, we will take the velocity of the star through the surrounding gas to be 20 km s^{-1}. Thus $r = 4 \times 10^4 / n_0^{1/2}$ AU. The model parameters are summarized in Table 1. We see that a star ejecting mass should be preceded in its passage through a dense cloud by a shell a few thousand AU away from it. The emission star HD 250550 illustrated in Herbig's (1960) review of A and B emission stars shows a shell to one side which might be formed in this way. We now estimate the shape of the shell in the star's wake.

The above analysis does not consider the development of the shell perpendicular to the star's motion. We will study this phase of the shell's properties using the model described in some detail and applied to early-type stars by Weaver *et al.* (1977). Weaver *et al.*

TABLE 1

A. OBSERVED PROPERTIES OF R MONOCEROTIS AND NGC 2261

Distance = 700 pc
Angular size of nebula = 2′
Linear size of nebula ≈ 80,000 AU
Distance of star from nebula apex ≈ 9000 AU
Radial velocity of R Mon = −27 km s^{-1}
Radial velocity of CO = 10.5 km s^{-1}

B. VALUES USED IN MODEL

v_i = ejection velocity from star = 200 km s^{-1}
v_0 = relative velocity of star and gas = 20 km s^{-1}
n_0 = particle density of cloud = 10 cm^{-3}
$\dot{M}$ = mass-loss rate from star = $4 \times 10^{-8}\ M_\odot\ \text{yr}^{-1}$

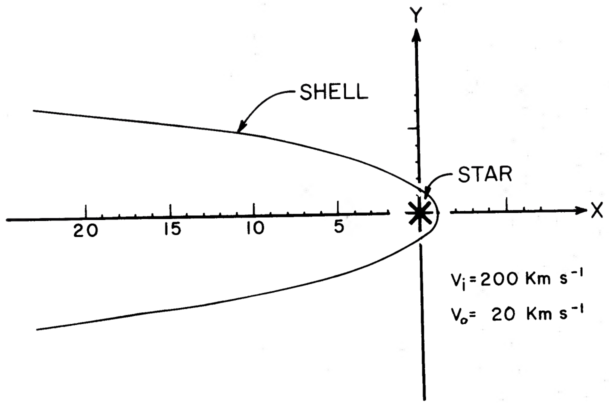

FIG. 2.—Shell surrounding star. Units on x and y axes are in 10^4 AU.

show that the shape of the shell boundary is given approximately by

$$y = \left(\frac{40\pi v_i}{33 v_0}\right)^{1/4} (\beta x)^{1/2}, \qquad (2)$$

where y is the distance away from the axis of the shell, defined by the direction of the star's motion, and x is the distance behind the star, measured along the axis of the nebula. (A similar result can be deduced directly from dimensional arguments.) We now require that this solution match that found for the shell directly ahead of the star which we deduced in equation (1). Thus we arrive at the final result for the shape of the downstream boundary:

$$y = \beta + \left(\frac{40\pi v_i}{33 v_0}\right)^{1/4} (\beta x)^{1/2}. \qquad (3)$$

Integrating equation (3) gives a value for the swept-up mass of $10^{-8}(v_i/v_0)^{1/2}L^2\beta n_0 \, M_\odot$, where L is the length of the nebula, and L and β are measured in units of 10^3 AU. For R Mon and NGC 2261, using the parameters chosen earlier, $\beta \approx 10^4$ AU, and the shell mass is thus $\sim 0.02 \, M_\odot$. Figure 2 shows y plotted for the values of the parameters we have used above.

We estimate the shell density by balancing the internal gas pressure in the shell against the stellar wind dynamic pressure. Using the same mass-loss rate as before, $n_s T_s \approx 7 \times 10^5 v_i/r^2$, where T_s is the temperature of the shell in K; v_i is in km s^{-1}; and r, the distance from the star, is in units of 10^3 AU. The energy input to the shell from the wind and swept-up interstellar matter is relatively small. Because the density is high, we assume that cooling is rapid and the shock is isothermal. For $T_s \approx 10$ K (from the observations of Loren *et al.*), $r \approx 10^4$ AU, and $v_i = 200$ km s^{-1}, we find a shell density of $n_s \approx 10^5$ cm^{-3}.

Observationally, we have the following information about the circumstellar environment. The CO emission found by Loren *et al.* suggests a CO column density of 5×10^{17} cm^{-2} or an H_2 column density of 1.6×10^{21} cm^{-2}. The visual obscuration suggests a dust optical thickness greater than 1 and less than 10. Taking $\tau_{\text{dust}} \approx 5$, a grain cross section of 2×10^{-9} (Allen 1973), and a dust/gas ratio of 10^{-12} gives a hydrogen column density of 2.5×10^{21} cm^{-2}. The agreement between these two estimates of the column density encourages us to believe that there is nothing anomalous about the dust/gas mixture and will help us set limits on the properties of the shell.

Since dynamically we require a shell particle density $\sim 10^5$ cm^{-3}, the shell thickness required to produce the observed column density is $\sim 10^{16}$ cm or $\sim 10^3$ AU. This is smaller than the observed distance of the shell from the star (10^4 AU) and is not implausibly small. We must now consider whether such a shell thickness is reasonable. The mass of the shell would be $\sim 0.3 \, M_\odot$, a factor of 10 larger than the amount of swept-up material from the H II region. A stellar mass-loss rate of $4 \times 10^{-8} \, M_\odot$ yr^{-1} is also too small to plausibly supply the shell. A remaining possibility is that it is residue from the star's formation. Larson (1972) has in fact suggested that R Mon represents a young star still deeply embedded in matter left over from its formation. Therefore, we suggest that the nebulosity NGC 2261 is produced by the dissipation of the circumstellar matter left over from the formation of R Mon. If true, this would make further study of the shell especially interesting.

It has been pointed out by Brück (1974) and others that NGC 2261 does not obey Hubble's law for reflection nebulosities in that the nebula is too large and bright for the star. The nebula is also bluer than the star (Greenstein and Oke 1977). As Stockton *et al.* have pointed out, these results are readily understood qualitatively if the star lies behind a shell as seen from the Earth, as our model suggests.

Some mention should also be made of the faint nebulosity on the side of R Mon opposite NGC 2261. This has been interpreted as a structure similar to NGC 2261, but heavily obscured and made difficult to see because of projection effects (Stockton *et al.*). In the model proposed here, the fainter nebulosity would be merely light from R Mon illuminating dust in the cloud through which R Mon is moving. We have made preliminary observations of NGC 2261 with the Five College Radio Astronomy Observatory millimeter-wave telescope. While the CO line is seen clearly toward R Mon and north into NGC 2261, it weakens considerably south of R Mon, suggesting a fundamental asymmetry in the nebula's shape.

IV. R MONOCEROTIS AND NGC 2261

We can now compare these results to the observations for R Mon and NGC 2261. Brück's (1974) photometry shows that the stellar condensation is roughly 13″ from the tip of the nebulosity. Most estimates of the distance of R Mon place it 700 pc away (Johnson 1968). At 700 pc, 13″ corresponds to a projected distance of 9100 AU. Equation (1) gives the stand-off distance of the shell as 10^4 AU if the cloud through which the star is moving has a density of 15 cm^{-3} and $v_0 = 20$ km s^{-1}, values in rough agreement with the CO observations and the optical spectroscopy. Depending on the orientation of the star's velocity vector, the projected stand-off distance will underestimate the distance given by equation (1). Projection effects will also alter the angle of the cone's apex. If the true apex half-angle is δ, the observed half-angle ϕ is given by $\tan \phi = \tan \delta / \sin \psi$, where ψ is the angle between the axis of the cone and the line of sight. Equation (3) can be used to give a rough estimate of δ; one finds that $\delta \approx 15°$, except in the immediate vicinity of the star where it becomes very large. Herbig (1968) measured a half-angle of $\sim 35°$ at the tip of the nebula. However, the half-angle of the entire nebula is considerably smaller, being closer to 20°. This requires a projection angle of $\sim 40°$.

The simple model described above is thus qualitatively able to explain the shape, size, and basic luminous features of R Mon and NGC 2261. We will see below that two other cometary nebulae may have a similar interpretation.

V. MODELS FOR THE V1057 CYGNI AND FU ORIONIS COMETARY NEBULAE

The model for R Mon and its associated nebula NGC 2261 may also apply to the stars V1057 Cygni and FU Orionis, for which there are both visual data and detailed CO spectral-line observations. Details of the visual and optical observations can be found in Bechis and Lo (1975), Bechis (1976), Grasdalen (1973), and Herbig (1966, 1976). The millimeter-wave CO maps of both V1057 Cyg and FU Ori show that these nebulae have CO mass distributions similar to their optical forms, suggesting strongly that these conical nebulae are not simply unusual lighting effects. If the latter were the case, then there should be no difference between the CO emission observed inside the illuminated cometary nebula and that observed just outside it. But for V1057 Cyg and FU Ori, this is not the situation. In view of their similarities to NGC 2261, we consider in more detail these two nebulae.

Analysis by Bechis (1976) of the nebulae associated with V1507 Cyg and FU Ori suggests that each is better represented by a hollow shell than by the more uniformly filled cone described in Bechis and Lo (1975). If the V1057 Cyg cometary nebula is a shell caused by the star's plowing through a surrounding dust cloud, then the path of motion of the star is nearly along our line of sight. If the short-lived 1720 MHz OH emission seen several years ago from V1057 Cyg (Lo and Bechis 1973, 1974) came from a locally dense and excited region close to the star—such as the leading edge of the star's "bow wave"—then that region would be expected to have a velocity close to that of the star. The CO emission from the gas and dust surrounding it and comprising the cometary nebula should indicate the radial velocity of the medium through which V1057 Cyg is moving. Since the OH velocity was $+1.3$ km s^{-1} and the CO velocity is $+4.1$ km s^{-1}, the star apparently has a relative velocity through the cloud toward the Earth of about 2.8 km s^{-1}. Using the mass-loss rate $4 \times 10^{-8}\, M_\odot$ yr^{-1}, a possible ejection velocity of 80 km s^{-1} deduced by Grasdalen (1973), and the H_2 density $n_0 = 1.1 \times 10^4$ cm^{-3} found by Bechis and Lo (1975), equation (1) gives the distance from the star to the shell as $r \approx 1700$ AU (2.5×10^{16} cm).

Interferometric measurements of the position of the OH-emitting region (presumably the apex of the shell ahead of the star) indicate that the region was coincident with the star to within 1″ (Lo and Bechis 1974). If the distance to V1057 Cyg is taken as 600 pc, 1″ corresponds to about 9×10^{15} cm. Because the orientation of the star's velocity vector, and of the major axis of its cone, is nearly along our line of sight ($\psi = 19°$), the foreshortened angular separation corresponds to a linear distance $r \leq 2.8 \times 10^{16}$ cm. This agrees well with the stand-off distance of the shell ahead of the star computed above. We now calculate the other dimensions of the nebula, using $\beta = 2.5 \times 10^{16}$ cm, $v_i = 80$ km s^{-1}, and $v_0 = 3$ km s^{-1} as above. Bechis and Lo (1975) estimate an upper limit to the length of the nebula of 1.3×10^{18} cm. Using the observed value for the width of 8.3×10^{17} cm, equation (3) gives a value for the length of about 4×10^{17} cm, three times smaller than the above upper limit but still reasonable, given the uncertainties involved.

The mass and volume of the shell associated with V1057 Cyg can be determined in a manner similar to that for R Mon. The shell volume works out to be about 3.3×10^{53} cm^3, in good agreement with that found by Bechis and Lo (1975) and close to the volume of the shell around R Mon. However, because the cloud density around V1057 Cyg is higher (10^4 cm^{-3}), the shell mass is greater than that found for R Mon and has a value of 6 $M_\odot$, again in satisfactory agreement with the mass deduced by Bechis and Lo.

In the case of FU Ori, the microwave radial velocity information is not as complete or accurate as that for V1057 Cyg, partly because the alignment of its cometary nebula (and hence its velocity vector) is more transverse to our line of sight. FU Orionis is remarkably similar to V1057 Cyg in most respects (Herbig 1960; Grasdalen 1973), and it is not unreasonable to ascribe to it a similar mass-loss rate and ejection velocity. A value for v_0 is not available, so the value used for V1057 Cyg (~ 3 km s^{-1}) is used. With an initial H_2 density $n_0 = 1 \times 10^4$ cm^{-3} (as found by Bechis 1976), equation (1) gives the distance from the star to the shell as $r = 2700$ AU (4.1×10^{16} cm).

Herbig's (1960) photograph shows the star to be roughly 7″ from the tip of the nebulosity. At the assumed distance to FU Ori of 600 pc, this corresponds to about 3500 AU (5.2×10^{16} cm), in fairly good agreement with the value calculated above. Using $\beta = 4.1 \times 10^{16}$ cm, $v_i = 80$ km s^{-1}, $v_0 = 3$ km s^{-1}, and an observed width for the nebula of about 1.4×10^{18} cm (Bechis 1976), equation (3) then gives a value for the length of about 6×10^{17} cm—within a factor of 2 of the value estimated by Bechis.

The mass and volume of the FU Ori shell can be determined in a manner similar to that for R Mon and V1057 Cyg. The shell volume works out to be about 5.1×10^{53} cm^3 (in good agreement with that found by

Bechis 1976). With the observed cloud density, the shell mass is found to be about 9 $M_{\odot}$, again matching well the mass derived by Bechis (1976).

VI. SUMMARY

A model in which a star ejecting matter into a dense cloud through which it is moving appears able to give good agreement with the observed properties of NGC 2261 and the two cometary nebulae V1057 Cygni and FU Orionis. For the latter two objects, CO molecular-line observations further substantiate a model in which the nebula is a shell formed of swept-up gas. For NGC 2261, high-resolution CO mapping would be highly desirable. Our model predicts that, immediately around the star, the CO line velocity produced in the shell should match that of the star but differ from that outside the visible nebulosity. It would also be helpful to have better optical radial velocities, especially for R Mon. Perhaps near-infrared observations where the dust might not be so optically thick could help determine the star's radial velocity. Comparison of the optical line profiles with models of a star with a cool expanding shell would be interesting, as would calculations of the light distribution in conical reflection nebulae.

Our model clearly does not apply to all reflection nebulosities around young stars. In particular, the biconical nebulae such as the Egg Nebula (Ney 1977; Ney *et al.* 1975) and the Red Rectangle cannot be explained by our mechanism. Growing evidence, however, suggests that these may represent evolved objects (Calvert and Cohen 1978), while the close proximity of R Mon to the young clusters NGC 2244 and 2264 suggests it may be extremely young. It seems prudent to consider the possibility that at least some of the cometary nebulae are physical structures and not simply illumination effects.

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THOMAS T. ARNY and KENNETH P. BECHIS: Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003