Shadowplay in Hubble’s variable nebula

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Summary. A reappraisal is made of Hubble’s variable nebula in the fresh knowledge that it is an illuminated cavity swept by the outflow from the young star, R Monocerotis. The old idea that the variability is due to shadows cast on the reflection nebula by clouds moving near R Mon remains good. Study of the two best observed shadow events shows the clouds responsible to have been filamentary, with angular motions suggesting an origin at the protostellar disc within 1 AU of the star and an outward velocity of several tens of kilometres per second. Their hydrogen density and mass were in excess of \( 7 \times 10^8 \) cm\(^{-3}\) and \( 4 \times 10^{-11} \) \( M_\odot \), respectively. Similar shadow eruptions occurred roughly once per year during the period of observation.

In addition, consideration is given to a pattern that has persisted in the quiescent nebula throughout the last 70 years. It is suggested that this is the shadow of a second group of filament loops, further from R Mon, some of which can be seen directly in the nebular fan. These filaments are much more massive than those responsible for the variability, each loop containing roughly \( 5 \times 10^{-3} \) \( M_\odot \) of material, and slower moving, at less than 12 km s\(^{-1}\). If they were formed near R Mon, their initial density must have been above \( 6 \times 10^7 \) cm\(^{-3}\).

The origin of the filaments, and their part in the outflow, are discussed.

1 Introduction
The fan nebula NGC 2261, near the young star R Monocerotis, sprang to fame at the beginning of the century when it was discovered by Hubble to vary in shape and brightness month by month (Hubble 1916). Today R Mon is once again in vogue, as the source of a molecular outflow and of the high-velocity gas exciting Herbig-Haro 39.

The similarity between their spectra suggested that the variable nebula was predominantly reflected light from the star (e.g. Slipher 1918; Lampland 1931; Dibai 1967); an idea confirmed by subsequent polarization observations (e.g. Khatchikian 1958; Aspin, McLean & Coyne 1985; Warren-Smith, Draper & Scarrott 1987). The triangular outline of the nebula, variations in the reflected spectrum up the fan, and the distribution of molecular material

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around R Mon imply that the reflecting layer is the surface of a conical cavity with the star at the southern apex (Greenstein et al. 1979; Cantó et al. 1981; Bachiller, Cernicharo & Martín-Pintado 1987). Measurements by Jones & Herbig (1982) of the radial velocity and proper motions of the emission knots in Herbig-Haro 39, which lies close to the axis of symmetry of the fan, indicate that they are moving almost perpendicular to the line-of-sight. This suggests that the nebular cone is seen directly from the side.

Deep photographs, such as those of Herbig (1968) or Walsh & Malin (1985), show the nebula to be conical only at its southern tip; further north the sides become parallel, and remain so until they fade from view near Herbig-Haro 39. There is a matching molecular outflow to the south of R Mon (Cantó et al. 1981; Bachiller et al. 1987), parts of which are occasionally visible optically. It is not clear whether the darkness of the southern flow is due to foreground obscuration or to poor illumination by R Mon.

2 The variability

The most comprehensive study of the nebular variability was made by C. O. Lampland at Lowell Observatory, who took more than 900 photographic plates of the object between 1916 and 1951 (Duncan 1956). The best way to appreciate this data is to watch the cine film made from the plates by Richard Hall in the 1960s, again at Lowell. The film confirms the belief of Hubble and Lampland that the variability is due to dark patches moving across the nebula, and shows these movements to be systematic and repetitive; the patches generally appear to the north or north-west of R Mon, then track across the fan and up its eastern limb. There is evidence that the polarization pattern of the nebula changes during the passage of dark areas (Scarrott, Draper & Warren-Smith 1989).

The proper motion of some dark areas corresponds to a true velocity across the fan greater than the speed of light which, given that the object is a reflection nebula, has led many to conclude that they are the shadows of dusty clouds moving near R Mon (e.g. Bellingham & Rossano 1980). The same idea was explored by Graham & Phillips (1987) with regard to the nebula lit by R Corona Australis, while a slightly different model, involving a precessing circumstellar disc, has been proposed by Rudnitskij (1987) to explain variable nebulae generally.

In the case of R Mon, the shadow movements are well enough observed to indicate the size, shape and angular velocity of the clouds responsible, if the distance to the object and shape of the reflecting surface are known. In this work, the latter is taken to be a figure of revolution about an axis on the plane of the sky, with the outline of the fan as its cross-section, and it is assumed that R Mon is 800pc away (Jones & Herbig 1982).

The cine film shows many shadow events but only the two best observed, whose behaviour seems representative of many others, are described here. These, the events of 1934 and 1940, are illustrated in Figs 1 and 3, and the inferred shadowing clouds are shown in Figs 2 and 4. The shape of the reflecting cone is such that shadows are only produced by objects in the altitude range 35 to 55° (altitude measured relative to the cone equator).

The fact that the shapes of both shadowing clouds can be derived in a self-consistent way suggests that the conical geometry assumed for the reflecting surface is correct, at least to a first approximation. In particular, the upward bow of many dark patches (e.g. those seen on 1934 January 7, 1934 October 7, 1935 January 25, or 1939 November 18) is the expected light-travel-time signature of a rising shadow projected on to the cone's curved near face. Similar shadows falling on the far side of the cone would appear bowed downwards, and such dark shapes are faintly visible in the eastern half of the fan at the beginnings of 1934 and 1935. If real, these would imply both that the 1934 filament moved right around R Mon during the
Figure 1. The 1934 shadow eruption. The date of the observation is marked at the corner of each sketch.

event, and that the shadows in the brighter, west and central parts of the fan were on the near side of the cone, those in the east on the far side (Fig. 6). Some support is given to this idea by the fact that no shadows move smoothly across the boundary between these two areas; they all suffer a discontinuity there, and some, such as those in the 1940 event, simply stop.

The azimuthal angular velocity of the 1934 shadowing cloud, as indicated by the movement of the filament's trailing end in the spring and by the time available for it to have re-crossed in front of R Mon during the summer, was $\sim 2 \times 10^{-7}$ rad s$^{-1}$. That of the 1940 filament end fell from above $2 \times 10^{-7}$ to $\sim 1.5 \times 10^{-8}$ rad s$^{-1}$ in the space of 40 d. The movement of both clouds in altitude was upward and slow, at $\sim 10^{-8}$ rad s$^{-1}$.

If the 1940 cloud started from a Keplerian orbit and conserved angular momentum during its evolution, then the magnitude and rate of decline of its azimuthal velocity would imply that it originated at the protostellar disc 1 AU from R Mon, and was moving outward at roughly 15 km s$^{-1}$. If angular momentum was transferred out along the filament, then the origin must have been closer to the star and the outward velocity higher. At 1 AU from the star, the angular speed
Figure 2. The shadowing structure deduced from the 1934 event. Altitude is measured relative to the equator of the reflecting cone, azimuth relative to a line from R Mon to Earth. Shadows on the fan are only produced by objects within the altitude range 35° to 55°. The sequence shows the object at various Earth dates, given in days after 1933 October 31.

Figure 3. The 1940 shadow eruption.
Plate 1. The nebula as it appeared on 1984 February 2 photographed by D. F. Malin using the Anglo–Australian Telescope. Malin obtained this image from the original plate (published by Walsh & Malin 1985) using an unsharp mask technique to reveal the fine structure.
in altitude corresponds to a space velocity of only 1.5 km s$^{-1}$. The shape and motion of the 1934 cloud are consistent with it having developed in the same way.

Though only these two events have been studied closely, many others developed in a similar fashion, and all give the same impression of having been caused by shadowing clouds that were moving away from the light source.

Lower limits to the density and mass of the clouds can be derived from the requirement that they be opaque to visible light. If, as the model suggests, they are typically filaments whose cross-sectional diameter subtends $\sim 5^\circ$ at R Mon, and if they are assumed to stretch in a semicircle around the star at a distance of 1 AU and to have a normal gas-to-dust ratio, then their gas density, column density and mass must be in excess of $7 \times 10^8$ cm$^{-3}$, $9 \times 10^{20}$ cm$^{-2}$ and $4 \times 10^{-11} M_\odot$, respectively. Over the period of Lampland's study major eruptions occurred every 1 or 2 yr, implying a yearly mass-loss rate roughly equal to an individual filament mass.

This has, of necessity, been a rather cursory analysis of the shadows that pass across Hubble's nebula, the prime hindrance to further work being a lack of high-quality data. The variability deserves renewed study with modern instrumentation.

3 The quiescent nebula

Hubble and Lampland recognized that the quiescent nebula, across which the variability patches move, is covered by a complicated pattern of light. This pattern can easily be seen in a recent photograph of the object (Plate 1), and comprises three characteristic elements; fanwise cuts in illumination, such as that occurring 1 arcmin north of R Mon, sets of broad, parallel bands running across the nebula, and groups of narrow filaments curled inside it (Fig. 5). A plate of similar quality, taken in 1920 by Hubble with the Mt Wilson 100-inch telescope (Johnson 1966), confirms that the pattern has not changed noticeably in 64 yr.

It is difficult to see why the reflecting material should itself be distributed in such a strange way. A simpler explanation would be that the reflecting surface is homogeneous but unevenly illuminated; shadows again. There are two reasons for believing there to be material inside the cone that could cast such shadows.
First, the large cut-offs and banded areas in the pattern are correlated, the cut-offs simply being the edges of different band systems, and both kinds of feature stretch right to the limbs of the fan. This is consistent with their light being reflection from the cone walls. The narrow filaments, however, behave independently of the rest of the pattern and always lie well inside the fan, suggesting that their light may be reflected from a different body of material. In addition, the filaments are too narrow to have been reflected unblurred by the cone wall unless the reflecting layer there is thinner than seems likely. These observations point to the filaments being dusty strands inside the cone.

Secondly, it was noted earlier that the shape of the shadows crossing the fan imply its south-western part to be reflection from the front side of the cone, while that to the east is from the back. However, there is also a third feature, a diagonal bar running along the upper edge of the south-west region, that seems to vary independently of either area (Fig. 6). This may well be

Figure 5. A diagram showing the major elements of the static pattern in the nebula. It is derived from Plate 1 and the images of the nebula obtained by Strom et al. (1986) and Aspin et al. (1985).

Figure 6. The areas of the nebula thought to be due to reflection from the near and far surfaces of the cone, and from material inside it.
reflection from matter inside the cavity. Unfortunately, Lampland's photographs lack the resolution to show its detailed shape.

The type of structure that would produce the banded pattern as a shadow is indicated by the following points. First, the repeated linear motif in the pattern implies the structure to be filamentary and repetitive. Secondly, it should have some sort of cylindrical symmetry because the flow must grow laterally with distance up the cone axis. The simplest appropriate geometry is that of a helix expanding away from the star. Thirdly, the fragments of filamentary structure in the fan are consistent with such a helical filament only if the axis of that helix is itself twisted into a larger one (Fig. 8). These two components of the geometry will be referred to below as the 'small' and the 'large' helices.

Note that this section aims only to determine the general characteristics of the required shadowing object, and that the adoption of helices at this stage is primarily for computational convenience. It is not meant to imply that the filaments are exactly this shape. Just which aspects of the shadowing structure really are specified by the pattern will be discussed later.

A computer program was written to calculate the pattern that would result from this configuration. The model includes a simplified treatment of the scattering process at the cone walls, sufficient to give a qualitative match to the overall brightness distribution across the nebula. The filaments are assumed to have a circular cross-section and a sharp edge. Self-shadowing and the orientation of the bright side of the filaments relative to the observer are taken into account, but secondary illumination by scattered light is not. The shape assumed for the reflecting cone is the same as that used in the variability study.

After some adjustment to the shadowing structure shape, the result shown in Fig. 7 was obtained. Most features of the observed pattern are successfully reproduced, including the projection of the correct parts onto the near and far sides of the cone. The shape and dimensions of the shadowing structure are shown in Fig. 8. It has the simple overall geometry described above, but the details are empirical and not strictly regular.

The cause and effect of the model can be checked at only one place, where a part of the shadowing structure theoretically responsible for an important feature of the pattern can be seen directly in photographs. This is the southernmost group of visible filaments, which should

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**Figure 7.** The model nebula described in the text.
cut off illumination north of point A on the eastern edge of the fan (Fig. 5). The width of the filaments is consistent with the model, and drawing a line from R Mon through the apparent limb of the group does indeed lead to the cut-off.

It must, however, be emphasized that, even if the model is correct, some aspects of the shadowing structure geometry remain unclear. This is because the shadow pattern is sensitive only to those segments of the small helix loops near the cone walls, and the filamentary fragments in the fan are too sketchy to give much additional information. Thus it is unlikely that the small ‘helix’ really is a helix, since a series of short arcs around the same axis would cast the same shadow. On the other hand, those features of the structure geometry to which the pattern does respond are well constrained by the data. In particular, the regular spacing of the loops provided by the small helix, and the curling of the large helix, are essential ingredients for success.

An estimate of the physical parameters of these filaments may be obtained from the requirement that they be optically thick at the point shading the cone walls north of point A. Taking the filament radius and geometry from the model, and assuming a normal gas to dust ratio, yields a lower limit to the hydrogen density there of 6 × 10^{4} cm^{-3}. This corresponds to a mass per small helix loop, if they are complete circles, of more than 5 × 10^{-3} M_{\odot}. The spatial period of the loops near R Mon is several × 10^{16} cm so that, if they are assumed to be parts of an outflow from the star with a mass loss rate of, say, 10^{-5} M_{\odot} yr^{-1}, then a temporal period greater than 500 yr and an outward velocity below 12 km s^{-1} are implied. Taking this estimated speed to be the escape velocity at the filaments’ point of origin would put the base of the flow somewhere beyond 2 × 10^{14} cm (15 AU) from the star, in the outer regions of the circumstellar disc. If mass flow is conserved then the gas density in the filaments within a few × 10^{16} cm of the star must be in excess of 6 × 10^{7} cm^{-3}, and the column density across the diameter of a single filament more than 10^{23} cm^{-2}.
Firmer proof of this model can only be provided by direct imaging of the supposed shadowing filaments near R Mon. Most of these will be obscured optically but ought to be visible in infrared or, possibly, polarization images. Light reflected from the filaments will be polarized perpendicular to the radius vector from the star; polarization that will be lost, along with spatial information, by those photons scattered by foreground dust before escaping, but preserved by those that escape directly. Any filaments inside the cone should, therefore, show up as strands of high polarization, so it is interesting that complex filamentary patterns are present near the star in the polarization maps of Aspin et al. (1985).

4 Discussion

There is evidence of filaments in other outflows. Lynds 1551 IRS5, for example, is another young star that illuminates the cavity swept by its flow, though less fully than R Mon does the variable nebula. A deep R-band CCD image, obtained by Strom et al. (1986), shows what appear to be faint, curled filaments in the cavity, forming a pattern similar to that of the shadowing structure proposed for R Mon.

T Tauri is closely ringed by a small nebulosity, Burnham’s Nebula, which appears to have a ‘layered’ structure (Lorre 1975). Beyond a break in this ring to the west of the star is a much larger illuminated area, Hind’s nebula NGC 1555. Both nebulae are variable, which Lorre suggested was due to obscuring material moving near T Tauri. The banded shape of NGC 1555, its angular coincidence with the gap in Burnham’s nebula, and the layered structure of the latter, would all be consistent with Burnham’s nebula being a group of filaments casting shadows on to the surface of the molecular cloud.

R Corona Australis, a star associated with both a variable reflection nebula and a molecular outflow (Slipher 1918; Knox-Shaw 1920; Graham & Phillips 1987), has long been recognized as an object belonging to the same class as R Mon. The shape of the reflection nebula is, on a large scale, suggestive of a filamentary helix expanding away from the star, though the best photographs show the detailed structure to be much more complicated.

Lying near RCrA is an obscured star which illuminates the conical reflection nebula Herbig-Haro 100. This cone contains several looped filaments and the brightest area of reflection nebulosity has sharp, straight edges pointing back to the star, a typical shadow effect (see, for example, the photographs in Cruz-Gonzalez, McBreen & Fazio 1984 and Hartigan & Lada 1985). Indeed there are many reflection nebulae near young stars where, though filaments are not directly visible, it is obvious that the illuminating starlight is being partly blocked by something near the source. Often such nebulae are variable.

Independent proof that young stars drive off blobs of dense gas is provided by recent molecular line observations. Mitchell et al. (1988b) have discovered near-IR CO absorption from a blob in front of GL490, moving towards us at 13 km s\(^{-1}\). Measurements of the HCO\(^+\) \(J=3-2\) line show that the gas has a density of perhaps 10\(^7\) cm\(^{-3}\), and is confined to an area within several \(\times 10^{16}\) cm of the star. With the CO/H\(_2\) ratio derived by Storey et al. (1981), the observations imply a lower limit to the hydrogen column density in the clump of \(7 \times 10^{21}\) cm\(^{-2}\). Considering the uncertainties, these numbers are consistent with the parameters of a single filament in the structure casting the pattern in the variable nebula. R Mon and GL490 have similar IR luminosities, 660\(L_\odot\) and 1400\(L_\odot\) respectively (Imhoff & Mendoza 1974; Harvey et al. 1979), so their outflows should be comparable.

Observations of M8E-IR also reveal dense gas. Mitchell et al. (1988a) find not one, but several CO absorption components in front of this star, blueshifted by between 90 and 170 km s\(^{-1}\). Each absorbing clump has a column density similar to that of the single cloud in GL490 and there is reason to believe that this material lies within 100 \(\text{AU}\) of the star. It is
tempting to identify these absorption components with the variability filaments in Hubble's nebula, though direct comparison may not be wise since MSE-IR is twenty times more luminous than R Mon (Thronson, Loewenstein & Stokes 1979).

Returning to the particular case of R Mon, there are, according to this interpretation of the data, at least three different regimes in the outflow; the high-velocity gas seen in [S ii] observations (Brugel, Mundt & Buhrke 1984) which powers HH39, the strands rising within 1 AU of the star that cause the variability, and the massive, slow-moving filaments casting the pattern. The question is, how are these three elements related?

The first possible answer is suggested by the fact that some Herbig-Haro objects are made up of bright knots beaded along faint strands of emission; HH2, HH12 and HH39 are examples. Sometimes these strands seem to be wound around a central axis in a rough helix. Though this phenomenon is not yet understood, it seems likely that it results from the development of cooling or hydrodynamic instabilities in the bow-shock at the head of the outflow and along the flow boundary (e.g. Raga & Bohm 1987; Norman & Hardee 1988; Chakrabarti 1988). If this mechanism should produce relatively dense strands curled around the outflow, then the massive filaments near R Mon may have been formed as the wind from the central star pushed out through the dense circumstellar mass. The variability filaments could be torn from the circumstellar disc in a similar way. According to this idea, therefore, the various shadowing objects are secondary consequences of a 300 km s\(^{-1}\) primary outflow from the central object.

The second answer would hold that each element of the flow is driven by magnetic energy escaping from a particular radius in the accretion disc. This idea is prompted by the work of Heyvaerts, Norman & Pudritz (1988) on the radio structures in the Galactic Centre, where they propose that a differentially rotating central engine, possibly the accretion disc around a black hole, has thrown off magnetically dominated loops of gas into the surrounding material. According to their model for the ejection mechanism, which is developed by analogy with the Sun, the Galactic Centre object erupts roughly once per revolution and drives off the loops at near the escape velocity of the radius of origin. This would be consistent with both the pattern and variability filaments near R Mon.

Additional support for the latter idea comes from the work of Stepinski & Levy (1988), who find that the dynamo action in accretion discs is localized at certain radii, and liable to be oscillatory or unstable. In this case, waves of magnetic flux will rise periodically from various points in the disc, taking with them the surface layers where the gravitational energy density is smaller than that of the magnetic field. If the field emerging 1 AU from the star has a strength of 1 G, taking the values inferred for the proto-Solar nebula (Levy 1978) and from H\(_2\)O maser studies of protostars (Strel'Nitskii 1988) as a guide, then the density at which disruption occurs will be \(\sim 10^9\) cm\(^{-3}\). This is similar to the density of the variability filaments in R Mon.

The possibility that small-scale magnetic flux tubes control the flow of material from protostars has also been discussed by Glencross et al. (1989).

**Note added in proof**

Filaments are indeed visible in \(J\), \(H\) and \(K\)-band IRCAM images of the nebula north of R Mon (Aspin et al. 1988).

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References