Mon. Not. R. astr. Soc. (1979) 187, 761–768

Optical polarization map of Eta Carinae and the nature of its outburst

R. F. Warren-Smith and S. M. Scarrott *Department of Physics, University of Durham, South Road, Durham*

Paul Murdin *Anglo-Australian Observatory, PO Box 296, Epping,* * *NSW 2121, Australia*

R. G. Bingham *Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, Sussex BN27 1RP*

Received 1978 November 2; in original form 1978 August 1

Summary. The compact nebula Eta Carinae has been mapped in optical linear polarization with a seeing-limited technique. The polarization is the result of scattering from small Mie particles, and the inner part of the polarization map shows that the illuminating source is slightly extended. That is identified as a circumstellar ring, presumably of ejected material, illuminated in turn by the central star. The position of the ring is compared with the positions of known infrared sources. The polarization information supports Thackeray's suggestion that the outer part of the nebula is prolate and inclined at 70° to the line of sight; the scattering angles in that model can lead to the observed degrees of polarization, and the bipolar-type elongation is along the axis of the proposed circumstellar ring. It is suggested that the circumstellar ring was formed by overflow from the outer Lagrangian points of a close binary star, and that the obscuration during the historical outburst was small. In that case, the object was too faint to have been a supernova, but was brighter than cataclysmic variables known to be in binary star systems.

1 Introduction

The early history of the η Car phenomenon has been summarized by Walborn & Liller (1977). After the main outburst between 1836 and 1856 a relatively small but well-defined maximum in the light curve occurred in 1889. In 1893 the object had an early F absorption-line spectrum, possibly supergiant luminosity class, arising according to Walborn & Liller in an expanding shell ejected shortly before. Subsequently the absorption line spectrum disappeared while the emission-line spectrum, weakly present in 1893, intensified.

At maximum, the outburst was magnitude $V \sim -0.5$. η Car is associated with OB stars at a distance of 2.8 kpc (Walborn & Ingerson 1977) and so had an absolute magnitude of $-12.7 - A_V$, where A_V is the interstellar absorption.

---

[*] Present address: Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, Sussex BN27 1RP.

η Car is a compact, knotty nebula some 20 arcsec in diameter, elongated in position angle 135°. There is most probably a central star of spectral type about B1 (e.g. Craine 1974). This nebula, known as the Homunculus, is expanding and the proper motions of the inner condensations imply an ejection time about 100 yr ago. Considering also the spectral changes, the implication is that the Homunculus is the ejected shell of 1889. The Homunculus shows bright infrared emission, including the 10 μm silicate feature, and Mitchell & Robinson (1978) present a dust shell model for it. The present bolometric magnitude, using all wavelengths, is approximately equal to the visual magnitude at maximum (Westphal & Neugebauer 1969). It seems possible that the bulk of this dust originated in the recorded outburst and now serves to convert most of the radiation from the central source to infrared (Pagel 1969). On that hypothesis, the presently observed extinction $A_V = 4.1$ mag (e.g. Aitken *et al.* 1977) was not present at maximum. Taking E_{B-V} for the cluster Trumpler 16 as 0.44 mag (Feinstein 1969), and therefore an interstellar A_V of 1.3 mag, the absolute magnitude at maximum was probably not much brighter than −14.0. The implications for the classification of η Car are discussed in Section 4.

Thackeray (1956) discovered the polarization of the Homunculus photographically. Visvanathan (1967) measured the polarization of the Homunculus as a whole, in several wavebands, including the Hα emission line. These measurements were made photoelectrically with apertures which covered virtually the whole of the Homunculus. In this paper we report measurements of the optical linear polarization of the Homunculus with better than 1 arcsec resolution, showing the resolved pattern of polarization and its probable relation to the structure and development of the nebula.

2 Experimental details

The observations were made at the *f*/15 focus of the 3.9-m Anglo-Australian Telescope on 1978 January 17 with the Durham electronographic polarimeter. At the time of the observations, the seeing was estimated at ~0.8 arcsec FWHM. The polarimeter uses a Wollaston prism to analyse the light which is then recorded on a 4-cm electronographic camera (McMullan & Powell 1976). A sequence of four electronographs yields a polarization map after the electronographs have been digitized and computer processed.

In the data reduction, corrections are applied for measured photocathode non-uniformity, film non-linearity and microdensitometer drift. Emulsion non-uniformity is accounted for in our reduction technique.

The polarization map of the η Car nebula is shown in Fig. 1. Measurements have been made with an integration bin of 0.7 × 0.7 arcsec with a separation of 0.7 arcsec. The measurement at each point is represented by a line, the length of which is proportional to the observed degree of linear polarization and orientation parallel to the direction of the *E*-vector.

For each measurement, we calculate the error in the degree of polarization and in the orientation. These errors as shown include both systematic errors (e.g. emulsion non-uniformity) and the random error corresponding to emulsion granularity. The upper part of Fig. 2 illustrates the errors for various positions along the major axis of the Homunculus. The polarimeter and reduction technique are described more fully elsewhere (Warren-Smith 1979).

The results have been corrected for an interstellar foreground polarization of 2.4 per cent at PA 108° as given by Visvanathan (1967). The filter used for the observations was a broad band *V* filter (GG 455 + BG 38).

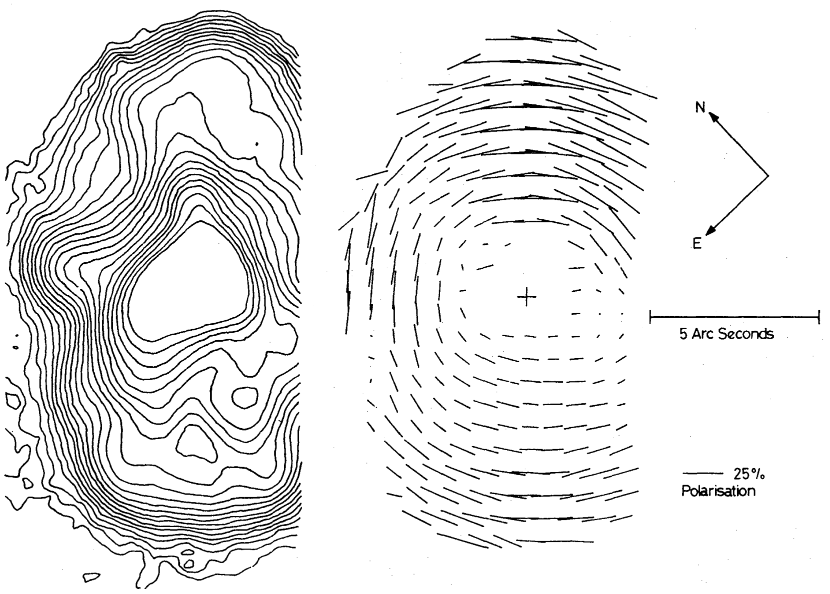

Figure 1. (Left) intensity contour map of the Homunculus, showing overall elliptical pattern with major axis NW–SE. Contours are 0.25 mag apart. Note the bar-like feature lying NE–SW across the minor axis. (Right) polarization map of the Homunculus. Lines are in direction of the electric vector and proportional in length to degree of linear polarization. Integration bins are 0.7 arcsec square. Note slight ellipticity of almost centro-symmetric pattern. Major axis of ellipticity lies along NE–SW bar-like feature.

Visvanathan (1967) measured the polarization of the Homunculus using apertures of 3–22 arcsec centred on the star. Through those apertures, the measured degrees of polarization are much lower than ours, as the slightly polarized central star is included, and the nebular polarization tended to cancel out in the presence of circular symmetry. Visvanathan's one

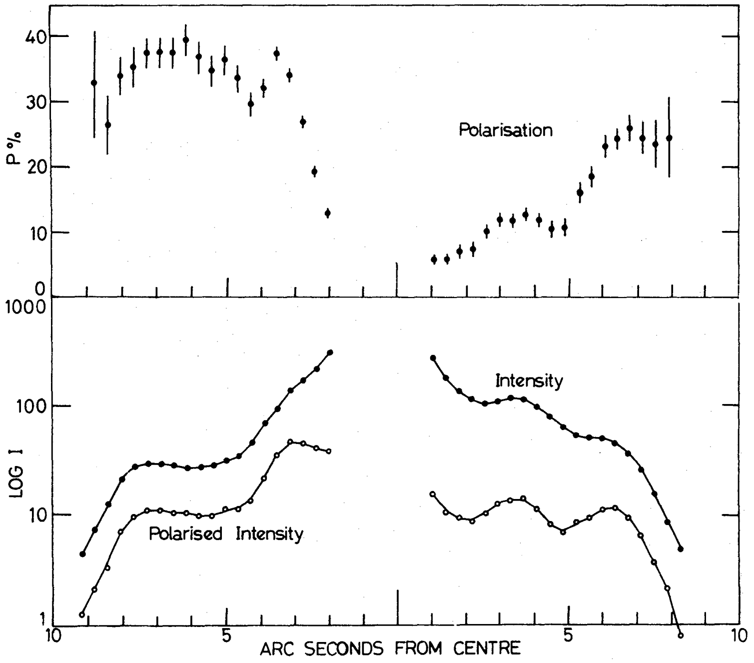

Figure 2. (Top) degree of polarization of a central strip along the major axis of the Homunculus. NW is to left, SE to right. Polarization shows a steady increase to the SE from the centre, but an abrupt increase to a plateau at 2.5 arcsec to the NW. (Bottom) intensity and polarized intensity along the major axis of the Homunculus. Intensity and polarized intensity are well correlated except 2–3 arcsec to NW where polarized intensity drops while intensity is increasing rapidly.

measurement in the head of the Homunculus with a 3 arcsec aperture gave a degree of polarization of 30 per cent, in a region where we obtain 35 ± 3 per cent. The difference is consistent with our better spatial resolution and different colour. We also have qualitative agreement with the earlier results of Wesselink (1962), particularly in the difference between his condensations *c* and *h* at opposite ends of the nebula.

3 Features of the polarization pattern

The electric vectors of the polarization of the Homunculus show an overall circular pattern, approximately centred on the presumed B1 star. The pattern is remarkably smooth both in degree of polarization and orientation, considering the irregular luminous structure of the image. The degree of polarization increases with distance from the centre of the pattern. The map is confirmatory evidence that the Homunculus is illuminated primarily by a central star, and we observed it by scattered radiation, the scattering centres being distributed throughout the nebula.

The polarization at the edge of the nebula is high, reaching up to 38 per cent. Three conclusions can be drawn from the polarization map.

(1) There is little intrinsic light emission (unpolarized) from the highly polarized areas. This is consistent with the observation of Aitken *et al.* (1977) that Brackett α emission comes almost entirely from a central source; but see also Thackeray (1961).

(2) The polarization orientation pattern is more a function of the overall geometry of the nebula rather than the distribution of scattering centres; at least the outer part is optically thin.

(3) Although the polarization surely arises from scattering, the nature of the scattering centres must be considered. Such strong effects might imply Rayleigh scattering, but that effect cannot be dominant, as the continuum intensity does not show the characteristic λ^{-4} dependence (Visvanathan 1967). Electron scattering is a possibility but, as Craine (1974) points out, there is insufficient electron optical depth to account for the observed polarization. We reject the electron scattering hypothesis also since:

(a) it implies an unrealistic amount of matter ejected in the η Car event ($\sim 10^3 M_\odot$);

(b) the recombination spectrum of the Homunculus is polarized (Visvanathan 1969) and so is scattered rather than intrinsically created;

(c) little light is created in the Homunculus (see (1) above).

Craine (1974) deduces the presence of dust grains particularly because of the large infrared excess in the continuum radiation and the presence of significant intrinsic reddening. Andriesse, Donn & Viotti (1978) present evidence for grains of size 1 μm in the Homunculus. We have considered the effect on the polarization of light scattered from Mie particles of such a size (Wickramasinghe 1973). The observed degree of polarization can be generated if the 1 μm grains are highly absorbing. The strongest polarization occurs in forward scattering. We present evidence below that *smaller* particles must be present.

Close inspection of the polarization pattern (Fig. 1) shows that the vectors are not quite centro-symmetric. The illuminating source appears to have extension along the minor axis of the Homunculus. Robinson *et al.* (in preparation) find that the 3.5–11.2 μm infrared radiation from η Car is extended along this axis. The infrared surface brightness distribution shows two distinct peaks of comparable intensity, separated by approximately 1.2 arcsec, but more complex distributions are not excluded by the observations. We have attempted to match several two-point-source models to the polarization map, using the chi-squared test as a criterion of fit. The models were not able fully to explain the pattern, but all fits required

1979MNRAS.187..761W

separate sources displaced along the minor axis of the Homunculus. We conclude that the illuminating source for the Homunculus is more complex than two point sources, but has extension along the minor axis of the Homunculus (PA 45°) of a few arcseconds. These results from the polarization are therefore consistent with the infrared observations. The optically illuminating and the infrared sources have at least superficially similar configurations and could be coincident.

Further inspection of Fig. 1 shows an asymmetry in the size of the polarization vectors, which are larger to the NW than the SE. This is shown in Fig. 2 where we plot degree of polarization along the major axis of the Homunculus as a function of distance from the centre. While the polarization to the SE increases uniformly to 25 per cent at 8 arcsec from the centre, the polarization to the NW remains small for 2.5 arcsec and rises abruptly to 32 per cent at 4 arcsec and remains near this higher value out to 10 arcsec from the minor axis. Traces at directions ±30° to the major axis show the same features as along the major axis.

The asymmetry of the polarization pattern is precisely of the same character as was observed for the bipolar reflection nebula M1–92 by Schmidt, Angel & Beaver (1978). M1–92 is distinguished from the Homunculus by an opaque dark cloud which cuts across the reflection nebula and is coincident with the area of low polarization abutting the abrupt rise in polarization to maximum. Schmidt *et al.* interpret the dark cloud as an optically thick ring centred on a bright star, and seen in projection against optically thin reflection nebulae illuminated along the axes of the ring. The startling similarity of polarization pattern between M1–92 and the Homunculus suggests a similar model with the variation that the optically thick ring must be luminous, rather than dark. The inclined ring can be seen as a bright bar along the minor axis of the Homunculus (Fig. 1, left). The front of the ring can be traced on the plot (upper part of Fig. 2) of the degree of polarization of the Homunculus along its major axis. The proposed model is illustrated in Fig. 3. The small degree of polarization in the inner 2.5 arcsec on the NW side may be ascribed to the nearer edge of the ring, seen by direct emission or with small scattering angles, and the steep rise may correspond to

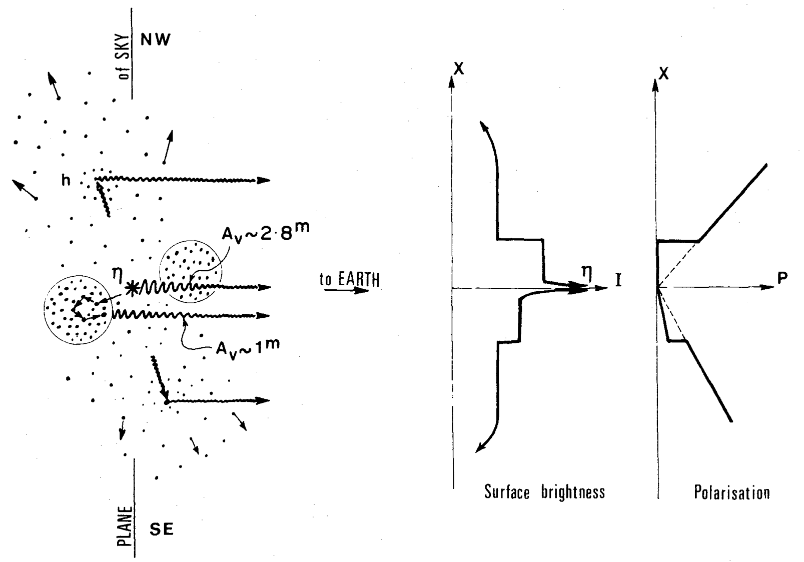

Figure 3. (Left) cross-section through the suggested model of η Car to describe features of the polarization map, expansion of the nebula and surface brightness distribution. The circles are cross-sections through the toroidal circumstellar ring postulated in text. Condensation *h* (optically thin reflection nebula) is expanding from η Car at 20° angle behind the plane of the sky. (Right) schematic polarization and surface brightness distribution deduced from model. *Cf.* Fig. 2.

the point where the line of sight passes the ring to the reflection nebula beyond. On the SE side, the distinction is expected, and is seen, to be less clear because the ring and nebula are seen in reflection at similar scattering angles, through some foreground nebulosity. (At present there are not sufficient data to describe the material and emission of the ring itself.) In the intensity profiles (lower part of Fig. 2), the ring can possibly be perceived by inflections in the curves. Obviously, the degree of polarization is a more reliable datum than intensity in an analysis of this kind because it is relatively weakly dependent on the density distribution of scattering centres (dust particles), both as regards reflection intensity and subsequent extinction. From the data given in Section 1, the circumstellar extinction (total minus interstellar) is estimated as 2.8 mag.

The geometry required by the polarization pattern and light distribution revealed by our observations (illustrated in Fig. 3) is identical to that postulated from radial velocity measurements of the 'head' of the Homunculus (condensation *h* 5 arcsec to the NW of η Car). Thackeray (1961) finds that *h*, chosen for highest polarization then known, was ejected from the centre of η Car and is receding. The tilt of the ejection axis is back from the plane of the sky by 20°. The highest degrees of polarization thus occur from backscattered light (turned through an angle 110°). This is incompatible with scattering from large ($1\,\mu$m) grains which polarize most effectively with scattering angles forward of 90°. Thus we are led to postulate that the Homunculus contains a population of small grains, size typically $0.1\,\mu$m or smaller, depending on the refractive index etc. For comparison, the mean size of grains in the interstellar medium is $0.15\,\mu$m (Greenberg 1966) but a population of smaller grains to $0.03\,\mu$m is also known from *Copernicus* ultraviolet observations (York *et al.* 1973). In all probability there is a range of dust particle sizes and refractive indices present in the Homunculus. The nature of the distributions can be investigated only by studying the polarization as a function of wavelength.

The source of the illumination of the bright optically thick ring must be the central bright star, and we interpret the ring as an extreme form of 'bright dark nebulae' (optically thick reflection nebulae) like the Thumbprint Nebula (FitzGerald 1974) and cometary globules (Hawarden & Brand 1976), but illuminated from within. It is tempting to speculate that the infrared sources observed by Robinson *et al.* (in preparation) represent not only the central source, but heating of the inner edge of the ring, seen at an inclined angle. (Robinson *et al.* have independently reached the same model for their observational data.) The illumination of the ring decreases rapidly with distance into the ring. We identify the inner part of the ring as the extension of the source of optical emission which we found from the asymmetry of the polarization pattern. Both the ring and central star contribute to light scattered from the optically thin reflection nebulae along the major axis of the Homunculus.

The similarity in polarization structure and light distribution between M1–92 and the Homunculus therefore arises because of the similar geometries of the nebulae. Differences arise because the nebula has a much brighter central source than the star which illuminates M1–92.

4 Conclusions

Schmidt *et al.* (1978) note the similarity between many planetaries and the bipolar nebulae and speculate upon the evolutionary link between them. They favour non-radial pulsations of the precursor (presumably of mass $1{-}2\,M_\odot$) as the fundamental cause of an asymmetry of the ejection mechanism at its equator and poles. η Car is widely regarded as a massive object, and indeed it is associated with Population I material (Walborn & Liller 1977). The central source has an effective temperature of 29 300 K and luminosity $\sim 10^7 L_\odot$ (Davidson 1971) and is presumably a massive star. Assuming that the exploding object was also massive, it was a very different star from the precursors of planetary nebulae. It is hard to see how it could undergo similar non-radial oscillations to produce a nebula with such similar geometry. However, Cohen & Kuhi (1977) have suggested that bipolar nebulae originate in a nova explosion in which an initially spherical expanding envelope interacts with a disk. Ejection is free along the poles of the disk, but constricted by swept up disk material in the direction of the disk's equator. We propose that the similar geometry of η Car to the bipolar nebulae arises because of the similar circumstances in which the originating explosion occurred.

The origin of a disk-like circumstellar cloud around η Car can be explained as : (a) an equatorially ejected ring or disk like that of a Be star (e.g. Struve 1931), (b) an accretion disk generated by Roche lobe overflow through the inner Lagrangian points in a close binary star, (c) an 'excretion' disk generated by overflow from the outer Lagrangian points of a close binary star. In view of the size of the disk which we see ($\sim 10^4$ AU) and the violence of the explosion of η Car (which would presumably destroy a small disk of size about 1 AU), we favour the latter explanation.

So far as we know, this is the first observational evidence that any cataclysmic variable brighter than classical novae has occurred in a binary star system. η Car was not a supernova, having quite a different light curve and probably being too faint (see Section 1); Tammann (1978) operationally defines a supernova by $M_V(\text{maximum}) < -16.0$. As indicated by Humphreys (1978), η Car and other objects may form a group with the Hubble–Sandage variables (Hubble & Sandage 1953). They are intermediate in absolute magnitude between novae and supernovae. Our polarization map indicates that binarity may play a role in their development – as well as that of novae and, possibly, supernovae (e.g. Whelan & Iben 1973).

Acknowledgments

We thank W. S. Pallister and J. F. Chesterman for help in reducing the data. Murdin thanks A. R. Hyland for communication of infrared data in advance of publication, and the participants of the Advanced School of Physics (Ettore Majorana) at Erice 1978 May for valuable discussions about the observational material presented here, particularly W. D. Arnett, R. Chevalier, R. Kirschner and S. van den Bergh. We thank B. E. J. Pagel for helpful discussion and comments on an earlier version of the manuscript. Time on the AAT was given to us by the UK Panel for the Allocation of Telescope Time. Warren-Smith was supported by a grant from the SRC.

References

Aitken, D. K., Jones, B., Bregman, J. D., Lester, D. F. & Rank, D. M., 1977. *Astrophys. J.*, **217**, 103.
Andriesse, C. D., Donn, B. D. & Viotti, R., 1978. *Mon. Not. R. astr. Soc.*, **185**, 771.
Cohen, M. & Kuhi, L. V., 1977. *Astrophys. J.*, **213**, 79.
Craine, E. R., 1974. *Astrophys. J.*, **191**, 105.
Davidson, K., 1971. *Mon. Not. R. astr. Soc.*, **154**, 415.
Feinstein, A., 1969. *Mon. Not. R. astr. Soc.*, **143**, 273.
FitzGerald, M. P., 1974. *Astr. Astrophys.*, **32**, 465.
Greenberg, J. M., 1966. In *Nebulae and Interstellar Matter*, eds Middlehurst, B. & Aller, L., University of Chicago Press.
Hawarden, T. G. & Brand, P. W. J. L., 1976. *Mon. Not. R. astr. Soc.*, **175**, 19P.
Hubble, E. & Sandage, A., 1953. *Astrophys. J.*, **118**, 353.
Humphreys, R. M., 1978. *Astrophys. J.*, **219**, 445.
McMullan, D. & Powell, J. R., 1976. IAU Coll. 40, *Applications astronomiques des recepteurs d'images a reponse lineaire*, p. 5-1, eds Duchesne, M. & Lelievre, G., Pub. Observatoire de Paris, Meudon.

Mitchell, R. M. & Robinson, G., 1978. *Astrophys. J.*, **220**, 841.

Pagel, B. E. J., 1969. *Astrophys. Lett.*, **4**, 221.

Schmidt, G. D., Angel, J. R. P. & Beaver, E. A., 1978. *Astrophys. J.*, **219**, 477.

Struve, O. 1931. *Astrophys. J.*, **73**, 94.

Tammann, G. A., 1978. *Mem. Soc. astr. Ital.*, **49**, 315.

Thackeray, A. D., 1956. *Observatory*, **76**, 154.

Thackeray, A. D., 1961. *Observatory*, **81**, 99.

Visvanathan, N., 1967. *Mon. Not. R. astr. Soc.*, **135**, 275.

Walborn, N. R. & Ingerson, T. E., 1977. *Sky Telesc.*, **54**, 22.

Walborn, N. R. & Liller, M., 1977. *Astrophys. J.*, **211**, 181.

Warren-Smith, R. F., 1979. *Thesis*, University of Durham.

Wesselink, A. J., 1962. *Mon. Not. R. astr. Soc.*, **124**, 501.

Westphal, J. A. & Neugebauer, G., 1969. *Astrophys. J.*, **156**, L45.

Whelan, J. & Iben, I., 1973. *Astrophys. J.*, **186**, 1007.

Wickramasinghe, N., 1973. *Light Scattering for Small Particles and Applications in Astronomy*, Hilger Press, London.

York, D. G., Drake, J. F., Jenkins, E. B., Morton, D. C., Rogerson, J. B. & Spitzer, L., 1973. *Astrophys. J.*, **182**, L1.