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THE PECULIAR OBJECT HD 44179 ("THE RED RECTANGLE")

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ABSTRACT

A strong infrared source detected in the AFCRL sky survey is confirmed, and is identified with the binary star HD 44179, embedded in a peculiar nebula. *UBVRI* and broad-band photometry between 2.2 and 27 μ are combined with blue, red, and near-infrared spectra, polarimetry and spectrophotometry of the star, and a range of direct and image-tube photographs of the nebula, to suggest a composite model of the system. In this model, the infrared radiation derives from thermal emission by dust grains contained in a disklike geometry about the central object, which appears to be of spectral type B9–AO III and which may be in pre-main-sequence evolution. Two infrared emission features are found, peaking at 8.7 and 11.3 μ, the latter corresponding to the feature seen in the spectrum of the planetary nebula NGC 7027. The complex nebular structure is discussed on the basis of photographs through narrow-band continuum and emission-line filters. The polarization data support the suggestion of a disk containing some large particles. No radio continuum emission is detected.

Subject headings: binaries — infrared sources — nebulae — stars, individual

I. INTRODUCTION

In a systematic photographic survey by one of us (M. C.) of infrared sources seen in the AFCRL sky survey (Walker and Price 1975), a number of interesting identifications have been made on the *National Geographic Society–Palomar Sky Survey* prints. One such source coincides with a ninth magnitude star embedded in nebulosity. The object is AFCRL 618–1343 = HD 44179 = BD $-10°1476$. The reality of the rocket infrared source was confirmed by ground based photometry in 1973 October, and direct photographs of the nebula were secured in 1973 November on the Kitt Peak 4-m reflector.

From 1973 November until 1974 March, a wide range of observational techniques was applied to this object. This paper describes these observations and suggests a composite model of the system based upon all the available data. The categories of observation discussed below are : § II, photography of the nebula; § III, spectroscopy; § IV, spectrophotometry; § V, broad-band photometry; § VI, infrared spectrophotometry; § VII, polarimetry; § VIII, radio observations; and § IX, the binary nature of HD 44179. Each section carries the names of those who have contributed to the observations.

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II. PHOTOGRAPHY OF THE NEBULA

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At the position of the infrared source, the Palomar prints show a closely nebulous star in the blue, and a crisp, rectangular object in the red (figs. 1*a* and 1*b* [pl. 3]). Direct photographs of the nebulosity were obtained in 1973 November and December at the prime focus of the Kitt Peak 4-m reflector. These plates, and subsequent ones taken with the 4-m and other telescopes, were intended to investigate the detailed structure of the "red rectangle," both in the continuum and in a variety of emission lines. Figure 1*c* shows the nebula through a broad red (RG 610) filter (15-minute exposure, O98-02, 1″–2″ seeing), and *f* shows a 30-minute exposure, also on O98-02 emulsion, in Hα + [N II], using a narrow-band filter (90 Å). In order to provide information on the central portions of the nebula, figures 1*d*, 1*e*, and 1*f* present a sequence of 90 Å passband Hα + [N II] photographs with exposures of 1, 6, and 30 minutes, respectively. The spikes first become apparent in the 6-minute exposure. A 6-minute exposure with a 90 Å bandpass filter centered at λ6470 in the continuum reveals essentially everything seen of the nebular structure in the 6-minute Hα exposure, and a 30-minute, 90 Å bandpass filter which isolates the $\lambda\lambda$6730 [S II] doublet shows no difference from the same length of exposure in Hα. However, a 90 Å bandpass photograph in the blue at λ4400 in the continuum, using the Kitt Peak No. 1 92-cm reflector with a Carnegie image tube, shows only a stellar image. A second (broad) blue plate taken at the prime focus of the Lick 3-m reflector reveals only a faint suggestion of nebulosity about the star.

Several other photographs have been secured of the nebula with various filters: a 93-minute near-infrared exposure ($\lambda_{eff} \sim 8500$ Å; hypersensitized I-N plate, RG 8 filter) on the 76-cm telescope of Leuschner Observatory at Berkeley only faintly indicates the northern pair of spikes, although adjacent star images have appreciable dimensions; a 30-minute yellow photograph (103aG plate, O64 filter) with the 92-cm refractor of Lick Observatory begins to show all four spikes emerging from the image of HD 44179. To investigate the region in which the sodium D-lines arise (see § III), a Kron tube was used on the Mount Hopkins 1.5-m telescope; the star image is slightly extended N–S into an elliptical nebulosity, rather like the appearance in the shortest Hα exposure (fig. 1*d*).

Extracting the salient features from this wide range of photographs, we may summarize the character of the nebulosity as follows: in the blue, a very weak amorphous nebula is present, very close to the star; in the yellow, a bright, small elliptical nebulosity surrounds the star, and this oval structure is seen in the D-lines, whereas the spikes are not, only becoming visible in a broad filter; in the red, the nebula shows an inner, bright, apparently rectangular core close to the star, with prominent bright spikes emanating symmetrically from its corners. Both rectangle and spikes are continuum features rather than line structure; in the near-infrared the spikes are weakly visible. The highly symmetrical appearance of the nebulosity is striking, and much detail is apparent beyond the bright rectangular core; for example, there is a second, fainter nebulosity present within the north and south quadrants which terminates sharply and linearly, parallel to the shorter edges of the rectangle. This fainter nebulosity meets the spikes at four small, bright knots which also limit the extent of the brightest portions of the spikes. The spikes persist beyond these knots but with a much reduced surface brightness. The nebula is about 40″ in N–S extent, although wispy extensions can be traced further out.

It should be noted that the spikes are not merely telescopic diffraction effects, for they maintain essentially the same appearance both in the Palomar Schmidt (with north–south and east–west diffraction patterns) and in the Kitt Peak 4-m reflector (with patterns rotated 45° to the cardinal directions). Figure 1 includes purely stellar diffraction patterns from the 4-m plates along with the images of HD 44179.

III. SPECTROSCOPY

ANNE COWLEY, WILLIAM M. FAWLEY, E. A. HARLAN, AND G. H. HERBIG

The spectroscopic material consists of 12 plates and an echelle spectrogram of HD 44179. Seven plates were taken at the coudé focus of the Lick Observatory 3-m reflector, two in the region λλ5800–6800, three in the region λλ7600–8600 at 34 Å mm^{-1}, using a cooled Varo intensifier, one covering λλ5600–6200 at 17 Å mm^{-1}, and one centered at Hα with a dispersion of 10 Å mm^{-1}. Two plates were taken on the 2.1-m reflector at Kitt Peak using the feed for the coudé spectrograph; these cover λλ5200–6800 at 25 Å mm^{-1} and λλ3600–5000 at 17 Å mm^{-1}. Two plates were obtained on the coudé auxiliary telescope of Lick Observatory in the region λλ5800–6800 at 33 Å mm^{-1}. A spectrogram was obtained with the Wisconsin 91-cm reflector using an echelle spectrometer (Schroeder and Anderson 1971) and a Carnegie image intensifier; this was centered at λ5890 and covered roughly half the spectrum between 5400 and 6400 Å. Sensitometric calibration was that of Anderson and Schiffer (1975).

The blue plate taken at Kitt Peak is very narrow, but shows that no emission lines are present in this spectral region. The hydrogen lines are broad absorptions, and a weak narrow interstellar K-line is present. The collection of red plates shows Hα to be a strong narrow emission centrally placed in a broad absorption; narrow sodium D-lines are present in emission. Na I λ5889 is weaker than the component at λ5895, although the reverse is to be expected. It is possible that interstellar absorption overlies the Na I emission producing this anomaly, although it is more likely that the region producing the lines is optically thick so that both lines are completely saturated.

At 10 Å mm^{-1} the structure of Hα is quite complex; the absorption is steep on the blue side but shallow and prolonged on the red, while the central sharp emission core is superposed on much broader emission wings within the overall absorption. The Wisconsin echellogram also shows He I λ5876 in absorption, and suggests that the D-line emissions are superposed on absorption features (fig. 2). In the near-infrared there are no emission lines; lines of the Paschen series appear in absorption as do those of O I λλ7771–7775 and 8446. No diffuse interstellar features are seen throughout the region from blue to near-infrared.

According to the HD catalog, the spectral type of star is B8. An objective prism plate, at 108 Å mm^{-1} in the blue, taken with the Curtis Schmidt at CTIO in late 1967, shows an apparently normal late B giant, classified independently by Houk and by Cowley as B9 II–III. The absorption strength at Hα is that expected from a star of type late B to early A, while in the near-infrared a type of AO III is appropriate. A spectrum of θ Aur (B9.5pv) taken at Wisconsin with the same echelle spectrograph used for HD 44179 shows He I λ5876 to be of comparable strength in the two stars, confirming a late B spectral type. Radial velocities have been determined from the emission lines in the red and from the absorption lines in the blue and the near-infrared. The velocities are Hα + 19.3, Na I λ5895 + 20.4, Na I λ5889 + 20.8 km s^{-1} in the red (errors ± 0.7), while the mean radial velocity from the Paschen lines and the O I absorptions in the near-infrared is +18 ± 2 km s^{-1}, and from eight hydrogen lines in the blue is 19 ± 9 km s^{-1}.

No definite statements can yet be made concerning the spectrum of the nebula, but a 30-minute red exposure at the coudé focus of the Lick 3-m reflector fails to show even the presence of Hα emission, in accordance with the photographic information on the similarity of nebular structure in Hα and in the red continuum.

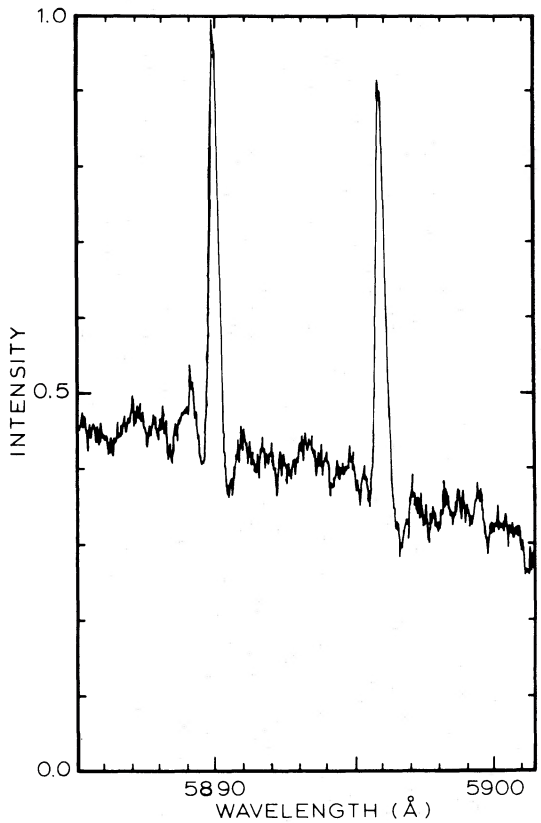

FIG. 2.—Direct intensity tracing of the Wisconsin echelle spectrogram of 1973 December 16–17 in the region λλ5885–5901, showing the D lines. In this plot, the exposure due to scattered light and image tube phosphor dark glow have been subtracted, in intensity, after processing through the characteristic curve obtained from sensitometric strips applied to a plate from the same glass blank as used for the stellar spectrogram and developed with it.

IV. SPECTROPHOTOMETRY

CHRISTOPHER M. ANDERSON, WILLIAM M. FAWLEY, ROGER O. JAKOUBEK, FRANCIS H. SCHIFFER III, AND HYRON SPINRAD

On the night of 1973 December 20–21, low resolution spectrophotometric observations of HD 44179 were obtained with the Washburn Observatory 41-cm reflector and computer controlled scanner. The observations were made with a 40 Å bandpass at the 17 standard wavelength points of Oke (1965) in the range λλ3390–5840 with a 7′ beam. Because of the prohibitively low slew rates of this telescope in the subzero (°F) conditions, it was not possible to obtain a full set of standard star observations for extinction and instrumental-sensitivity calibration. Instead the nearby unreddened (Crawford 1963) B9 star HD 44037 was also observed, and both stars were reduced to monochromatic magnitudes $AB(\lambda^{-1}) = -2.5 \log F_\nu + C$ on the system of Oke and Schild (1970) with mean extinction coefficients and instrumental sensitivities. The night was of good quality and the colors, defined as $AB(\lambda^{-1}) - AB(1.8)$, of HD 44037 are in excellent agreement with observations of other stars of its spectral type obtained with the standard procedure. We thus feel that these colors can be considered good to about ± 0.04 mag.

The results of this spectrophotometry are given in table 1 and plotted as a function of frequency in reciprocal microns in figure 3. In this figure the open triangles are the observed colors of HD 44037 and the filled circles are those of HD 44179. The latter is substantially reddened. If we assume that the intrinsic spectral energy distribution in the Paschen continuum of HD 44179 can be represented by that of HD 44037, the color excesses can be determined. The $E(B - V)$ is approximately 0.5 and the excess between 1.8 and

TABLE 1

LOW RESOLUTION SPECTROPHOTOMETRY

λ	λ^{-1}	HD 44037	HD 44179	Reddening Curve	HD 44179 minus Reddening
3390.........	2.950	+0.70	+2.20	+0.81	+1.22
3448.........	2.900	+0.72	+2.22	+0.78	+1.28
3509.........	2.850	+0.73	+2.17	+0.76	+1.25
3571.........	2.800	+0.71	+2.11	+0.74	+1.22
3636.........	2.750	+0.71	+1.69	+0.71	+0.83
3704.........	2.700	+0.58	+0.89	+0.68	+0.07
3862.........	2.589	−0.16	+0.37	+0.62	−0.38
4032.........	2.480	−0.37	+0.29	+0.54	−0.36
4167.........	2.400	−0.35	+0.26	+0.50	−0.35
4255.........	2.350	−0.32	+0.24	+0.45	−0.31
4464.........	2.240	−0.25	+0.19	+0.37	−0.26
4566.........	2.190	−0.23	+0.18	+0.34	−0.23
4785.........	2.090	−0.18	+0.15	+0.25	−0.15
5000.........	2.000	−0.12	+0.14	+0.18	−0.08
5263.........	1.900	−0.04	+0.08	+0.09	−0.03
5556.........	1.800	0.00	0.00	0.00	0.00
5840.........	1.712	+0.14	−0.01	−0.07	+0.08

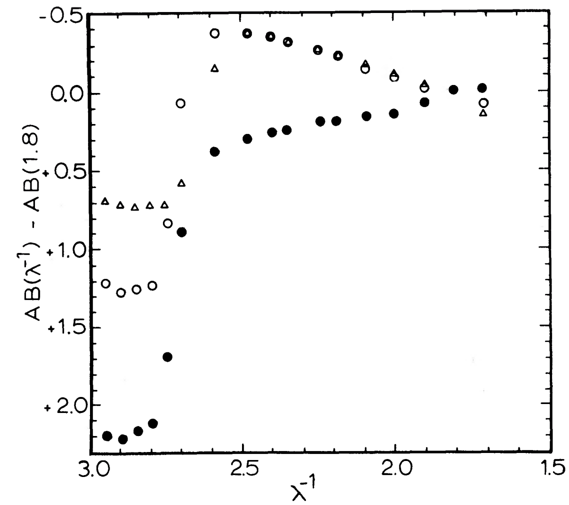

FIG. 3.—The observed and computed monochromatic colors as a function of frequency in reciprocal microns. *Open triangles*, the observations of HD 44179; *open circles*, the de-reddened colors of HD 44179.

2.4 μ^{-1} is 0.61. The latter value, along with the mean field reddening curve of Anderson (1970) which is given in column (5) of table 1, can be used to remove the reddening. The results of this process are shown in figure 3 by the open circles, and in column (6) of table 1. It is seen that the Paschen continua are in quite good agreement up to 2.48 μ^{-1}. However, the Balmer continuum of HD 44179 is depressed by about 0.5 mag relative to HD 44037. Considering the temperature inferred from the presence in absorption of He I, this Balmer jump, if stellar in origin, would imply a very large surface gravity (Mihalas 1970). On the other hand, 40 Å bandpass observations at the two points at 2.589 (between H8 and H9) and 2.700 μ^{-1} (which includes H14 to H18) are usually seen to be depressed with respect to either models or very narrow band scans, and this depression increases with higher gravity due to the Stark broadening of the hydrogen lines. In this case these points are significantly brighter in HD 44179 than in HD 44037. This could be an instrumental discrepancy (e.g., due to poor centering of HD 44037 in the diaphragm), but should be kept in mind.

Spectrophotometric data on HD 44179 were obtained on two nights in 1974 February with the prime focus scanner and 91-cm reflector of the Lick Observatory. The entrance aperture was 1 mm, corresponding to 42″ on the sky. On the first night, HD 44179 was observed with a 30 Å bandpass at wavelengths used by Hayes (1970) longward of 7000 Å. Air-mass corrections for this night were empirically determined by observations of Hayes's standard stars. On the second night, 90 Å bandpasses were used and the star was scanned at 100 Å intervals between 6000 and 10800 Å. Air-mass corrections (ranging between 0.02 and 0.05 mag) for this night were derived by interpolation between values given by Hayes;

TABLE 2

SPECTROPHOTOMETRIC OBSERVATIONS WITH 30 Å BANDPASSES

λ(Å)	Mag	λ(Å)	Mag
7100......	8.36 ± 0.03	9832.....	8.09 ± 0.07
7530......	8.35 ± 0.05	10256.....	7.93 ± 0.08
7780......	8.43 ± 0.06	10400.....	8.02 ± 0.11
8090......	8.37 ± 0.04	10610.....	7.90 ± 0.08
8370......	8.34 ± 0.06	10796.....	7.75 ± 0.13
8708......	8.25 ± 0.04	10870.....	7.80 ± 0.15

NOTE.—Monochromatic magnitudes are tabulated: −2.5 log (F_ν/F_0) with $F_0 = 3.46 \times 10^{-20}$ ergs s^{-1} cm^{-2} Hz^{-1}. Errors are 1 σ of the mean magnitudes.

the night was relatively transparent and without smog interference from San Jose.

The relative monochromatic magnitudes obtained from the 30 Å data appear in table 2 along with errors of 1 σ of the mean. Absolute fluxes for these measurements came directly from Hayes's calibration of γ Gem. For the 90 Å data, absolute fluxes were derived by the following method: monochromatic magnitudes were computed relative to γ Gem (because of the large number, these are not presented in tabular form but can be supplied on request). For those 90 Å regions containing Hα or Paschen lines, we have assumed that the equivalent widths of these lines in γ Gem (A0 V) are equal to those of α Lyr. The widths in α Lyr were determined from 10 Å bandpass scans kindly made available by L. Kuhi. This procedure of determining the flux depression probably is internally accurate to only 0.05 mag. Finally, absolute fluxes from the 90 Å data for γ Gem, and hence of HD 44179, were computed by interpolation between the wavelengths used by Hayes, making the above-described allowance for hydrogen line absorptions. The internal photometric errors (1 σ of the mean) for the 90 Å data are 0.05 mag or better below 10200 Å and increase to 0.10 mag at 10800 Å. Figure 4 presents all the

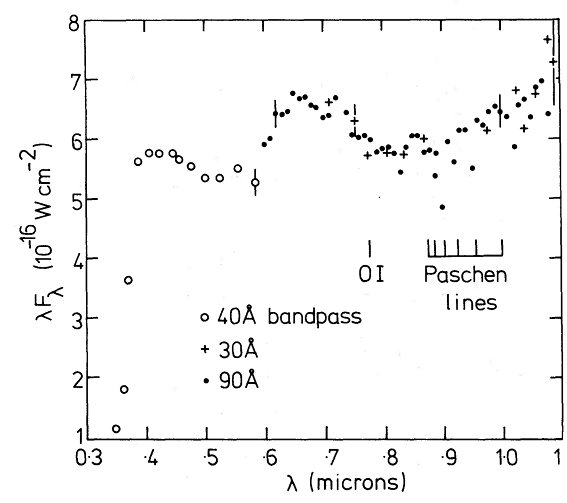

FIG. 4.—The combined spectrophotometry between 0.36 and 1.1 μ. Both axes are linear plots, and representative error bars (1 σ of the mean) are indicated, as are the positions of several absorption lines.

spectrophotometry between 3400 and 10800 Å in the form of a linear plot of λF_λ against λ.

The most remarkable features of the composite energy distribution of HD 44179 are the very broad apparent emission feature centered at 6900 Å and the general increase of flux between 8000 and 10800 Å. The depression at 7780 Å is most probably real and due to the absorption lines of the O I triplet near λ7774 (see § III). The curious bump in the distribution is also clearly seen in 2″ aperture observations of this object kindly obtained with the Cassegrain IDS scanner on the Lick Observatory 3-m reflector by H. Spinrad, H. E. Smith, and J. Liebert. Unfortunately these data are not as reliable as the spectrophotometry presented above because of cloudy conditions, and they have therefore not been shown in figure 4.

V. BROAD-BAND PHOTOMETRY

Martin Cohen, H. S. Hudson, K. M. Merrill, and B. T. Soifer

UBVRI photometry of HD 44179 was acquired on 1973 December 13 and 26 with the University of Minnesota–University of California, San Diego 1.5 m Mount Lemmon telescope using a 33″ circular diaphragm. The phototube was an RCA C31034 with a GaAs photocathode for red response and was operated in current mode. *UBV* and *R* are essentially the standard effective wavelengths and bandpasses, but *I* is somewhat shorter (0.82 μ) than that of Johnson, since the phototube response determines its long wavelength cutoff. The two sets of data are in excellent agreement and the magnitudes and photometric errors are presented in table 3.

Three sets of infrared photometric data were gathered in the period 1973 October to December with different aperture sizes. These comprise photometry between 2.2 and 18 μ with 4″ beams using a liquid-helium–cooled bolometer on the Lick 3-m reflector; between 2.2 and 22 μ with 11″ beams using a similar bolometer at Mount Lemmon; between 2.3 and 12.5 μ with 22″ beams using a photoconductor at Mount Lemmon. Observations of HD 44179 at 27 μ with 11″ beams were also obtained at Mount Lemmon on a very dry night in February. Table 4 displays these infrared magnitudes in three groups according to aperture. The total errors in these measurements (photometric statistics, uncertainties in calibrations, etc.) should not exceed ±5 percent from 2.2 to 12.5 μ,

TABLE 3

UBVRI Photometry of HD 44179 with 33″ Diaphragm, and 1 σ of the Mean Errors

Filter	$\lambda_{\rm eff}$(Å)	Magnitude
U..........	3600	+9.51 ± 0.03
B..........	4380	+9.22 ± 0.02
V..........	5475	+8.83 ± 0.02
R..........	6800	+8.27 ± 0.02
I...........	8200	+7.97 ± 0.03

TABLE 4

Infrared Photometry of HD 44179 with Different Beam Sizes

A. Rocket Data, 10′ × 3′ Beam

[4]	+0.78	[11]	−2.63	[20]	−4.18

B. Mount Lemmon 1.5-Meter Reflector, 22″ Beams, Photoconductive Detector

[2.3]	+3.19	[3.5]	+1.22	[4.9]	+0.09
[8.4]	−2.14	[11.2]	−2.63	[12.5]	−2.87

C. Mount Lemmon 1.5-Meter Reflector, 11″ Beams, Bolometric Detector

[2.2]	+3.47	[3.6]	+1.26	[4.8]	+0.27
[8.6]	−2.08	[10.8]	−2.38	[11.3]	−2.64
[12.8]	−2.80	[18]	−4.0	[22]	−3.9
[27]	−4.7				

D. Lick 3-Meter Reflector, 4″ Beams, Bolometric Detector

[2.2]	+3.53	[3.5]	+1.47	[4.8]	+0.60
[8.6]	−2.15	[11.5]	−2.56	[18]	−4.0

±15 percent at 18 and 22 μ, and ±25 percent at 27 μ, of which photometric errors alone contribute at most a few percent between 2.2 and 27 μ. Table 4 also includes the magnitudes obtained from the AFCRL rocket at 4, 11, and 20 μ. The differences in magnitude between the 11″ and 22″ data from 2 to 5 μ is almost certainly due to differing effective wavelengths caused by the responses of the germanium bolometer and the photoconductor; the former has a flat responsivity in this region, whereas the latter rises steeply at the shortest wavelengths in this range. Comparison of the various magnitudes in apertures from 4″ to 10′ × 3′ (that of the rocket survey) suggests that the infrared source is essentially pointlike, at least on a scale of a few arc seconds.

Figure 5 combines the *UBVRI* and infrared photometry into the energy distribution of HD 44179 in the form of λF_λ ($W\,{\rm cm}^{-2}$) against λ (microns). A blackbody curve is also shown for comparison.

In order to evaluate the reddening we assume that both components of the binary (see § IX) have the same spectral type, B9–A0 III. Section VII demonstrates the likelihood of large grains being present around the star, and there might, therefore, be a component of neutral extinction. However, a reasonable lower limit can be placed on the true fluxes by correcting the observations for purely interstellar reddening. In this manner we find $E(B-V) = 0.39$ and $A_V = 1.2$ (from Lee 1968 for $T_{\rm eff} = 10{,}000°$ K). Figure 5 shows broad-band fluxes de-reddened by this amount, again using Lee's tables (based on van de Hulst curve no. 15). Between *B* and *R*, the de-reddened curve has a slope like a Rayleigh-Jeans tail of a hot blackbody, but from *I* an appreciable near-infrared excess above this slope becomes apparent. This excess is also shown by the longer wavelength scanner spectrophotometry

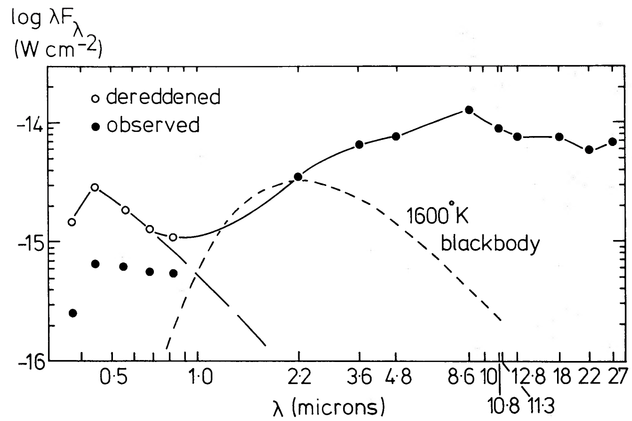

FIG. 5.—The composite energy distribution for HD 44179 between 0.36 and 27 μ, based on the broad-band observations. Both observed and de-reddened values of λF_λ are shown at the shorter wavelengths. Both axes are logarithmic and a blackbody curve is shown for comparison.

(fig. 4). It is possible to fit the Wien portion of a cool blackbody ($\sim 1600°$ K) into the de-reddened λF_λ distribution between about 0.8 and 2.2 μ in such a manner that the sum of the fluxes of this blackbody and of the Rayleigh-Jeans tail of the hot stellar component would roughly match the de-reddened observations from 3600 Å to about 2.2 μ. However, beyond 2.2 μ this simple blackbody curve cannot match the data, which present the appearance of a slowly rising broad distribution which reaches a peak somewhere near 8 μ. The composite λF_λ curve should be compared with that of HD 45677 (Swings and Allen 1971).

It is unreasonable to suppose that there is contamination of the broad-band near-infrared fluxes by emission lines (e.g., the Brackett series) when there is no evidence for emission lines of related species in the near-infrared spectra. Consequently there would appear to be a very broad yet relatively flat infrared continuum between 2 and 27 μ. This continuum is most probably due to thermal emission by dust grains at a range of temperatures and with a variety of compositions. There is strong independent evidence for dust near the star in the color and geometry of the nebula, in the large Balmer discontinuity, in the presence of spectral features near 10 μ (§ VI), and in the polarization data (§ VIII).

VI. INFRARED SPECTROPHOTOMETRY

K. M. MERRILL

Spectrophotometry covering the wavelength range 8–13 μ with a resolution of $\Delta\lambda/\lambda \approx 0.015$ was carried out during 1973 December with a cooled filter wheel spectrometer built at UCSD by F. C. Gillett. The observations, a total of four scans or 80 seconds total integration time per point, were taken with a 22″ beam at the UM–UCSD 1.5-m infrared telescope on Mount Lemmon, and were calibrated against α Tau. The averaged data shown in figure 6 have a statistical accuracy of better than ± 5 percent, although the absolute flux level is less certain.

Emission features are seen near 8.7 and 11.3 μ superposed on a smooth continuum which drops sharply from 8 μ and levels out beyond 10 μ. While far less complicated, this spectrum is strikingly similar to that of the planetary nebulae NGC 7027 and BD+30°3639 where the 11.3-μ feature, possibly due to mineral carbonates such as calcium magnesium carbonate (Gillett, Forrest, and Merrill 1973), is present at nearly the same strength relative to the continuum. The 8.7-μ feature, at best only marginally apparent in the two planetary nebulae spectra (where statistical uncertainty or a possible emission line prevents identification), is possibly due to mineral sulfates such as calcium magnesium sulfate which in the laboratory produce strong narrow absorption peaks in the vicinity of 9 μ (Lyon 1964). Consistent with an extremely low excitation region (as evidenced by the D-lines in emission), there is no evidence for the 9.0-μ [Ar III], 10.52-μ [S IV], or 12.78-μ [Ne II] lines seen in the planetaries.

VII. POLARIMETRY OF HD 44179

GEORGE V. COYNE

Polarimetric observations of HD 44179 were made in six spectral bands with a dual channel rotating half-wave plate polarimeter coupled to a NOVA computer. The observations are listed in table 5. They

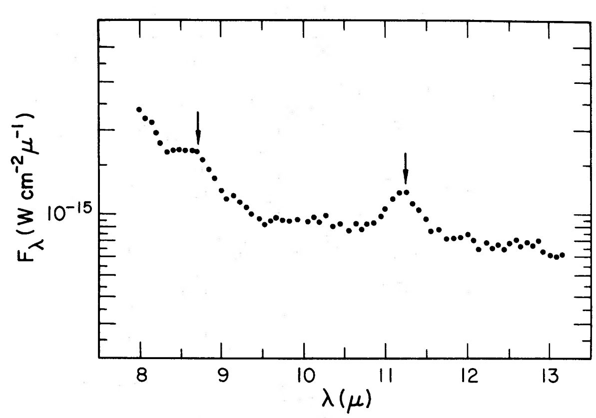

FIG. 6.—The 8–13 μ infrared spectrophotometry showing the two emission peaks.

TABLE 5

JOURNAL OF POLARIMETRIC OBSERVATIONS

$1/\lambda_0$ (μ^{-1})	Date 1973–1974	(percent)	ϵ_p	θ (degrees)	ϵ_θ	Δp* (percent)
2.72.........	Jan. 19	0.94	±0.05	41.6	±1.5	−0.01
	Jan. 23	0.98	±0.03	44.3	±0.9	−0.08
	Jan. 29	0.98	±0.03	44.0	±0.9	0.00
	Mean	0.97	±0.03	43.3	±1.4	...
2.32.........	Jan. 19	0.94	±0.02	39.6	±0.6	−0.02
	Jan. 23	0.96	±0.03	38.6	±0.9	−0.05
	Jan. 29	0.94	±0.01	39.7	±0.3	−0.01
	Mean	0.95	±0.01	39.3	±0.7	...
1.93.........	Jan. 19	0.94	±0.03	36.2	±1.0	−0.01
	Jan. 23	1.00	±0.04	37.2	±1.2	−0.05
	Jan. 29	1.03	±0.02	38.0	±0.6	0.00
	Mean	0.99	±0.05	37.2	±0.6	...
1.52.........	Jan. 23	1.07	±0.06	32.2	±1.7	−0.03
	Jan. 29	1.11	±0.18	37.1	±4.9	+0.24
	Mean	1.09	±0.08	34.7	±2.9	...
1.16.........	Dec. 8	1.38	±0.16	27.3	±3.5	+0.04
	Jan. 23	1.23	±0.04	29.5	±1.0	−0.05
	Mean	1.30	±0.08	28.3	±2.2	...
1.06.........	Dec. 8	1.26	±0.33	23.2	±7.8	+0.11
	Jan. 19	1.43	±0.31	22.7	±6.5	+0.08
	Jan. 23	1.38	±0.07	25.4	±1.5	+0.11
	Mean	1.36	±0.08	23.9	±1.6	...

* The measured sky-polarization corrections which were subtracted from the star-plus-sky data to obtain the polarization of the starlight listed in column (3). See text for explanation.

were made with the 1.5-m and 2.3-m telescopes of the University of Arizona. Corrections for instrumental polarization (less than $p = 0.05$ percent) have been applied. Corrections for the polarization of the background sky have been made by measuring at the four cardinal points at $15'' \pm 3''$ from the star with a $10''$ diaphragm (the same as that used for the star-plus-sky measurements). Among these four sky measurements, the polarization differed by less than 10 percent of its mean value and the flux did not differ at all. The average polarization and flux were used to determine the sky corrections listed in the last column of table 5. These are the product of the sky polarization, the flux ratio of sky to star-plus-sky, and $\cos 2(\theta_m - \theta_s)$, where θ_m and θ_s are the position angles of the measured (star-plus-sky) polarization and the sky polarization, respectively. The corrections are small except for the $I(1/\lambda_0 = 1.06\,\mu^{-1})$ filter where they are about 3 times larger than the average sky correction and of opposite sign. The sky correction at the $O(1/\lambda_0 = 1.52\,\mu^{-1})$ filter for January 29 is anomalous. These polarimetric results are independent of aperture used in the range $5''$ to $20''$.

In figure 7 are plotted the mean percentage polarizations and position angles of table 5. These are the observed values corrected for instrumental and sky polarizations. The observations, including the position angle rotation, can be explained if one assumes three components of the observed polarization: electron scattering in the stellar atmosphere, Mie scattering from large grains in a circumstellar nebula, and interstellar polarization.

In order to sample the interstellar polarization ($l^{\rm II} = 219°$, $b^{\rm II} = -12°$), the polarization at the G filter ($1/\lambda_0 = 1.93\,\mu^{-1}$) was measured for two stars within $6'$ of HD 44179 (for which $m_G = 8.7$ mag) with the following results: for HD 44219, $p = 0.02$ percent, $\theta = 129°$, $m_G = 7.7$ mag; for BD−10°1480,

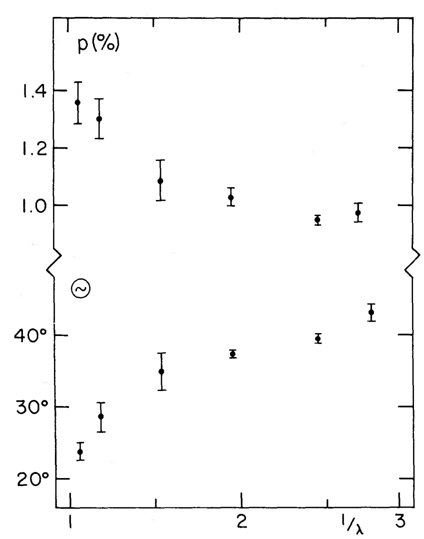

FIG. 7.—Percentage polarization (p) and position angle (θ) for HD 44179. The error bars give mean errors. The position angle rotation is due to a combination of electron scattering [$p = 0.95$ percent, $\theta = 42°$] and scattering from large grains [$p(\lambda)$, $\theta \approx 7°$].

TABLE 6

CORRECTED POLARIMETRIC DATA WHEN INTERSTELLAR AND ELECTRON SCATTERING POLARIZATION COMPONENTS HAVE BEEN REMOVED

$1/\lambda_0$ (μ^{-1})	2.72	2.32	1.93	1.52	1.16	1.06
p(%)	0.07	0.15	0.24	0.37	0.69	0.86
θ(°)	...*	6	7	9	7	3

* The resultant position angle at 2.72 μ^{-1} is indeterminate.

$p = 0.13$ percent, $\theta = 86°$, $m_G = 9.8$ mag. The distance to these stars is not known and, for want of more information on them, the interstellar polarization is taken as the average of the two measured values: $p = 0.08$ percent, $\theta = 108°$. In the catalog of Mathewson and Ford (1970) for seven stars which have $b^{II} < -8°$ and lie within 4° of HD 44179 at distances from 350 to 650 pc, the polarization ranges from 0.09 to 0.40 percent. If the distance to HD 44179 is about 400 pc (see § X), our estimate of the interstellar polarization from the measurement of two nearby field stars appears to be essentially correct.

Polarization by electron scattering is neutral. If we assume that the observations between 2.3 μ^{-1} and 3.0 μ^{-1} in figure 7 represent the electron scattering component ($p = 0.95$ percent, $\theta = 42°$) and subtract this and the interstellar polarization from the observed polarization, we obtain the results given in table 6. The mean polarization position angle (giving one-half weight to the value at $1/\lambda_0 = 1.06\ \mu^{-1}$ because of the anomalous sky corrections) is $7 \pm 2°$. Thus by removing the interstellar and electron scattering components we obtain a component with a well determined plane of polarization (the plane of the electric vector maximum) which is approximately parallel to the nearly north–south edge of the rectangular nebular core (see fig. 1*d* where a line corresponding to $\theta = 7°$ is drawn). Changes of 0.1 percent in the electron scattering and/or interstellar components of the polarization change the resultant position angle by less than 10°. This component of the polarization must be due to scattering by quite large nebular grains, since the maximum of the polarization curve has not yet been reached at $1/\lambda_0 = 1.06\ \mu^{-1}$, aligned at right angles to $\theta = 7°$.

VIII. RADIO OBSERVATIONS

HUGH M. JOHNSON, D. MATSAKIS, AND BEN ZUCKERMAN

HD 44179 was observed with the 36-m dish of the Haystack Observatory[1] on 1973 December 6 and 7, UT, in the 15.5 GHz continuum. A standard technique of beam-switching at 10 Hz was used to minimize atmospheric noise. The two beams were separated horizontally 0°.2, and each beam remained on source 32 s alternately, 10 times to constitute a scan. A total of nine such scans were made. The standard source DR 21 was observed each night with the same technique. Assuming that its flux density is 20.1 Jy at 15.5 GHz, the derived flux density of HD 44179 is -0.023 ± 0.025 Jy. Consequently only an upper limit to the strength of the source can be given.

Observations of HD 44179 were made on 1973 November 19, at a frequency of 8.4 GHz using the NASA–JPL Deep Space Network 64-m antenna at Goldstone, equipped with a right circularly polarized feed. Four drift scans were made through the position of the object. The average of these scans provides only an upper limit to the 8.4 GHz flux in a 2′.1 beam of 0.022 Jy (1 σ).

[1] Radio astronomy programs at the Haystack Observatory are conducted with support from the National Science Foundation.

IX. THE BINARY

FRANK HOLDEN

The star HD 44179 is a visual double, ADS 4954, discovered by Aitken in 1915. Since its discovery, it has been observed on 13 occasions and resolved on 11 (see table 7). The observations indicate genuine duplicity and obvious motion, and suggest that the components were of equal brightness between 1915 and 1947, but have had $\Delta m \approx 0.4$ mag between 1951 and 1962. The separation slowly decreased from a maximum of 0″.27 in 1921 to 0″.17 in 1947, but van den Bos was unable to resolve the pair in 1948 (implying a separation $\leqslant$ 0″.1). Subsequently the pair reopened and the separation when last resolved was 0″.21 in 1962. This scattered information does not enable the determination of an orbit.

Recent observations of HD 44179 have been made by Holden. The star was examined several times with the 92-cm refractor of Lick Observatory in late 1973, and with the 1.5-m reflector at Mount Wilson in early 1974. On none of these occasions was the seeing good enough to show duplicity of the star. The star was observed on 1974 April 10, 19, and 20, with good seeing using a 92-cm reflector at CTIO. The powers used were ×700, 1000, and 1700, but no duplicity was noted. Pairs with a separation <0″.2 were clearly resolved with the same telescope on April 10, and a strong upper limit of 0″.1 can be placed on the separation of HD 44179.

If the two stars are indeed of comparable brightness, then there are quite severe constraints on the spectral type of the companion. Throughout the region from the blue to the near-infrared, only a few absorption lines appear in the spectrum of HD 44179, and all of these are consistent with a late B or early A star. A late-type secondary, for example an M star, is precluded by the lack of molecular absorptions near 8000 Å. Equally, the presence of a hot star, for example an O star, is excluded by the *UBV* and scanner data which show no evidence of a continuum increasing to short wavelengths. If the early spectral type, B9–A0, is appropriate to the primary, then only the emission features at Hα and the D-lines remain unexplained, yet there is no significant difference in radial velocity between these emission lines and the absorption lines. Consequently, one is forced to conclude either that the companion has a spectrum close (B7–A2) to that of the primary, or that a simple

TABLE 7

Binary Observations of HD 44179

Date	Position Angle	Separation	Δm	Observer*	N†
1915.11....	141°6	0″30	0	A	3
1921.82....	143.8	0.27	...	A	2
1930.19....	114.5	0.24	0	A	1
1941.08...	168.8	0.20	0.2	B	1
1944.06....	214.8	0.23	0.2	B	1
1945.17....	203.0	0.20	0	B	1
1947.22....	174.2	0.17	0	B	1
1948.10....	...	< 0.1	...	B	1
1951.07....	120.1	0.16	...	B	1
1958.03....	340.8	0.16	0.4	B	1
1958.09....	351.9	0.20	0.5	B	1
1959.17....	346.4	0.19	0.3	B	4
1962.03....	356.3	0.21	0.4	B	2
1974.29....	...	< 0.1	...	H	3

* Observer: A = Aitken; B = van den Bos; H = Holden.

† Number of nights on which measurements were made.

interpretation of the duplicity in terms of two stars is invalid. It is, however, unlikely that starlight scattered, for example, from some gas cloud in the vicinity of the primary would have a brightness comparable to that of the star or a convincingly stellar visual appearance, as the observations suggest. Therefore, an interpretation of the duplicity in terms of two stars seems entirely reasonable. Given the presence of considerable dust near the star, it is not impossible that protracted obscuration of one component of a binary might occur, so that one or both of the disappearances of the companion (1948 and 1973–1974) may not necessarily be due to orbital aspect. Indeed it may be that the difference in magnitudes noted by van den Bos between 1951 and 1962 foreshadowed the onset of such an obscuring phase. This hypothesis implies that in the past HD 44179 may have undergone slow changes in magnitude of small amplitude ($\sim$0.5 mag); as yet there is no evidence of such variability. It should be noted that the position angles of the binary (table 7) have not always been close to the plane of the dust disk, so one can invoke occasional disappearances of the companion.

X. DISCUSSION

We conclude that HD 44179 consists of one or two stars of spectral type B9–A0 III, and that a very low excitation region, in which the Hα and D-line emissions arise, is also present. It will be convenient now to summarize the evidence that dust is associated with the system, after which the color of the nebula and its geometry can be more easily discussed. Clues to the presence of circumstellar grains near HD 44179 are as follows, with the relevant sections of this paper in parentheses: (1) the large Balmer jump coupled with the lack of obvious widespread obscuration on the Palomar prints (§ IV); (2) the gross excess of infrared radiation over the Rayleigh-Jeans tail of a hot blackbody (§ V); (3) the presence of narrow spectral features attributable to dust particles in the 8–13 μ spectrum (§ VI); (4) the polarimetric data suggesting the existence of large grains which scatter the starlight producing the unusual $p(\lambda)$ curve (§ VII); (ξ) the possibility of local obscuration having caused a disappearance of the companion of HD 44179 (§ IX; see also the discussion below of the masses of the stars in the binary).

Paradoxically, despite the presence of an embedded blue star the nebula does not possess appreciable blue continuum, nor does its light arise significantly from emission lines. That the nebulosity is bright in red continuum remains to be explained. It would appear that the rectangular aspect of the nebula is a product of the brightness of HD 44179—were the star much fainter, the nebula would be seen to narrow to a small waist in the vicinity of the star. Consequently the geometry of the nebula seems to be that of a biconical structure (with axis $\theta \sim 7°$) in which the spikes represent a cone of higher surface brightness than the inner nebulosity. The nebula might be regarded as another example of an "hourglass" cometary nebula; or magnetic fields and plasma confinement might be invoked, or rotation, especially in the light of the high degree of symmetry.

If we are confronted by a cometary nebula, then the canonical picture of the hourglass morphology is relevant (e.g., Cohen 1974), but the wealth of observational material available on HD 44179 elevates this picture from circumstantial argument to a far stronger case. The geometry implies that surrounding HD 44179 there is an equatorial disklike structure of gas and dust close to whose plane we lie; in this model the inner edge of the toroid restricts the diffusion of light from the central object except into two cones of semiangle about 30° around the normal to the disk. The infrared radiation suggests considerable dust is about HD 44179, and it would be most unreasonable to assume that only relatively large grains, which dominate the polarization near 1 μ, are present. Within the two cones, starlight suffers local reddening by an admixture of small and large grains before escaping from the vicinity of the disk, eventually to be scattered in our direction by an extensive enveloping halo of gas and perhaps small dust grains. The lack of aperture-dependence of the infrared fluxes suggests that only quite cold grains can be present in this halo ($T \leqslant 150°$ K). In this manner we can explain many of the features of the nebula, in particular the red continuum and the small nebulosity very close to the star seen in the blue (fig. 1*b*), in terms of scattering of reddened starlight. It should be noted that this would make HD 44179 the brightest star (visually) associated with a biconical nebula. Alternatively, the very symmetrical structure in the nebula might be explicable by a process of reconnecting magnetic fields following the collapse of an interstellar cloud from which HD 44179 was born (cf. the pattern of standing waves in fig. 1 of Priest 1973). There is one major restriction to be placed on a magnetohydrodynamic explanation, namely that no shock waves are involved in the system; this limitation arises from the lack of significant line emission within the nebula. However, in order to produce the strong red continuum and the spikes, it may be necessary to invoke both the reddening hypothesis and magnetic (and/or rotational) dominance of the overall structure. Although the 8–13 μ spectrum of HD 44179 has some similarities to those of two planetary nebulae, there is no justification for describing the nebulosity as a planetary, particularly since no radio continuum has been found.

Returning to the spectrophotometry, since photographs of the nebula indicate the presence of a strong continuum around 6500 Å but not in the near-infrared (~8500 Å), it is tempting to attribute the broad feature near 6900 Å to the nebula rather than to the star. This could, for example, be a feature in the scattering cross section of some circumstellar grains. It is not yet possible to make a definite statement about the origin of this feature; more spectrophotometry is planned using a variety of aperture sizes in order to define the precise contribution of the nebula to the spectrum.

An estimate of the distance of HD 44179 is clearly important. The simplest estimate can be made by assuming that the *UBV* data refer to a single B9 III star (and that the companion is presently hidden). this implies $M_V = -0.4$; and we find $V = 8.8$, $A_V = 1.2$ (see § V), $V_0 = 7.6$, and hence $D = 400$ pc. Perhaps more realistic estimates can be made by assuming that HD 44179 has the same *bolometric* luminosity as LkHα 208 or R Mon, stars also associated with conical or biconical nebulae which are bright infrared objects. Cohen (1973) gives $M_{\text{bol}} = -1.7$ for the former and -2.7 for the latter. For comparison with these objects, we require the total flux of HD 44179 ($\int_0^\infty F_\lambda d\lambda$). Since de-reddening the data increases the luminosity of HD 44179 by only 9 percent, we shall deal with the de-reddened spectral intensities (F_λ). A much more serious question relates to the unobserved radiation longward of 27 μ. A lower bound on this latter contribution (in the absence of spectral features) may be obtained from Appendix A of Cohen (1973), and yields an estimated 29 percent of the total luminosity beyond 27 μ. The appropriate values for the integrated spectral intensity in the ranges (0.36 μ, 27 μ) and (0.36 μ, ∞) are 2.23 (-14) and 3.13 (-14) W cm^{-2}. Comparison of the larger of these two figures with LkHα 208 gives a distance of 240 pc, and with R Mon, 370 pc. It would seem that a distance of 330 pc does justice to the three estimates above.

At 330 pc, the bolometric luminosity of HD 44179 is 1050 $L_\odot$, and the luminosity ratio of a 10,000° K blackbody, matched to the de-reddened data at *B* and *V*, to the observed spectrum between *U* and 27 μ, is 1:6. Replacing the blackbody by a model appropriate to a 10,000° K giant (e.g., Strom and Avrett 1965) reduces this ratio to 1:5 (of course allowance for energy beyond 27 μ increases the ratio). Thus arguing for a binary consisting of two normal B9 giants, both of which are presently visible despite their closeness in the sky, leads to a gross deficiency in the energy required to power the infrared emission. If one member of the binary is obscured now, but is another B9 giant, the deficiency is reduced to (>) 2.5. Only if the companion is both currently invisible and highly luminous can we escape this dilemma. From the observations of the binary we may attempt to estimate the sum of the masses of the two stars: provided that obscuration is responsible for one of the two "disappearances" of the companion, the period is no less than ~160 yr; for the apparent mean separation we take ~0″.2. This yields $(M_1 + M_2) \approx 11\ M_0$ and suggests that we may require stars which are too luminous for their masses. If the disappearances of the companion in 1948 and 1974 are indeed due to orbital motion, then $P \approx 26$ yr—or perhaps ~52 yr, depending on the orientation of the orbit—which gives $(M_1 + M_2) \approx 400\ M_0$ (or 120), an absurd situation. Taken in context, the association of a dust disk, the peculiar nebula, and the large infrared energy argue for the pre-main-sequence nature of HD 44179. This conclusion suggests that perhaps rotation is responsible for the nebular symmetry rather than magnetic fields, for in the latter situation it is difficult to reconcile confinement of gas and dust with the lack of significant line emission in the nebula.

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Note added in proof—A new blue spectrum of HD 44179 has been obtained by A. Cowley in 1974 October on the 1.8-m reflector of the Dominion Astrophysical Observatory. The plate covers the region λλ3600–4900 at 15 Å mm^{-1} on fine grain emulsion, and is well widened. Very narrow, weak emission components of calcium H and K are seen, at radial velocity $+21.3 \pm 1.4$ km s^{-1} (cf. the velocity of the D-lines in § III), with red-displaced absorptions (velocity $+55.1 \pm 2.6$ km s^{-1}) similar to, but stronger than, those seen near the D-lines (fig. 2). The difference in radial velocities between the sharp calcium emissions and the adjacent absorptions is the same as the corresponding shift measured for the D-lines. The stellar velocity, determined from 12 hydrogen lines, is $+26.9 \pm 4.3$ km s^{-1}. Many weak absorption lines typical of late B stars are present in the spectrum, but four weak C I absorption lines are present with radial velocity $+36.8 \pm 4.2$ km s^{-1}, different from the stellar velocity. No C II lines are seen, and no other late B star is known to show these C I lines, which are the four strongest lines in the appropriate multiplet tables.

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Second note added in proof.—W. Liller has very kindly sampled 12 blue plates in the Harvard plate collection showing HD 44179 between 1897 and 1974, and has found no evidence of variability. The total range of blue magnitudes is 0.20 mag, and the mean error of a single measurement is 0.05 mag.

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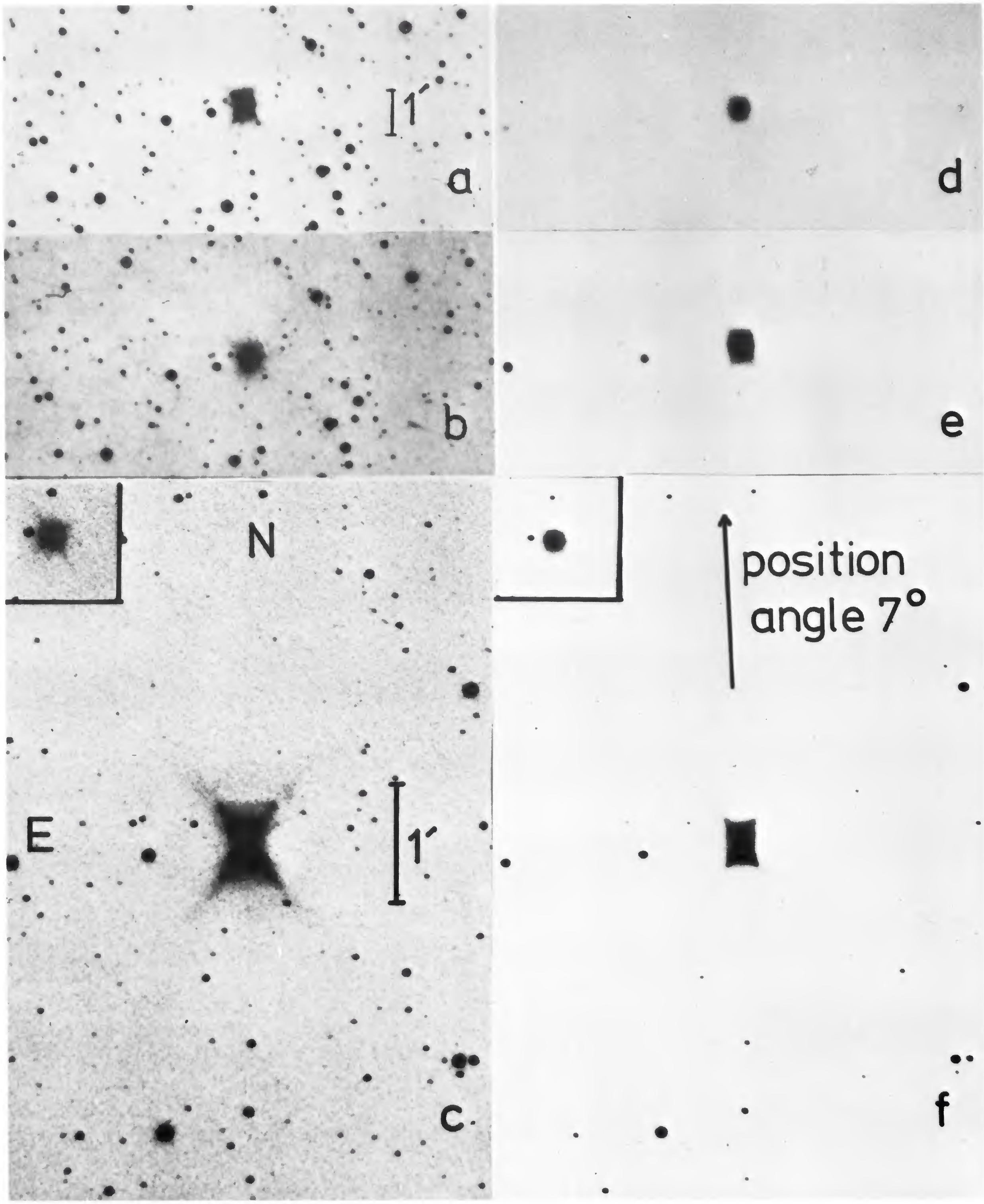

FIG. 1.—(*a*) and (*b*) are red and blue reproductions with permission from the *National Geographic Society–Palomar Observatory Sky Survey* prints; (*c*), the 4-meter RG 610 plate; (*d*), (*e*), and (*f*), the 4-meter Hα + [N II] plate sequence with exposures 1, 6, and 30 min, respectively. The line marked in (*d*) indicates the direction of grain polarization of light from HD 44179 (see § VII). To show clearly how little the nebular structure in (*e*) and (*f*) is a function of telescope diffraction pattern, insets are included, with the correct orientations, of the image of a star comparable in brightness to HD 44179 and from the same original plates. The spikes are at $\theta \sim 43°$, 162°, 224°, and 343°, with nebulosity in the acute angles.

COHEN *et al.* (*see* page 179)