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THE PRECATACLYSMIC NUCLEUS OF ABELL 41[1]

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ABSTRACT

Photometric observations of the 15th magnitude central star of the planetary nebula Abell 41 have revealed it to be an ultra–short-period binary system. The *U* and *B* light curves exhibit broad, 0.15 mag humps that recur with a period of 2^h43^m. The variations are most probably due to the heated hemisphere of a low-mass main-sequence companion of the very hot primary star. All of the observations are consistent with a binary system containing a sdO primary of $\sim 0.6\ M_\odot$ and a dM companion of 0.1–0.3 $M_\odot$; the companion is so close to the primary that its facing hemisphere is heated to $\sim$40,000 K.

No evidence for mass transfer has been observed; thus, the central star of Abell 41 is the detached binary with the shortest known orbital period. Loss of angular momentum through gravitational radiation, however, will be sufficient to bring the main-sequence secondary star into contact with its critical Roche surface in less than 2×10^9 yr, initiating mass transfer and cataclysmic activity. The existence of Abell 41 provides strong support for the suggestion that all cataclysmic variables are descended from wide binaries that have suffered catastrophic angular-momentum loss through ejection of a planetary nebula.

Subject headings: nebulae: individual — nebulae: planetary — stars: binaries — stars: dwarf novae — stars: variables

I. INTRODUCTION

Several authors (including Vauclair 1972; Ritter 1976; Paczyński 1976, 1981; Webbink, see Gallagher and Starrfield 1976; Livio, Salzmann, and Shaviv 1979; Meyer and Meyer-Hofmeister 1979) have concluded that catastrophic mass and angular-momentum losses from an initially wide binary are necessary to account for the formation of extremely close binaries containing a white-dwarf component (such as detached white dwarf/red dwarf systems like V471 Tau and interacting cataclysmic binaries). According to the proposed scenario, if the original binary separation is sufficiently large, the primary star can evolve to red-giant dimensions before encountering the secondary main-sequence star. If the evolutionary expansion is rapid enough, the secondary star may then be engulfed by the outer layers of the primary, forming a "common-envelope" binary. The secondary would begin to spiral in, transferring its orbital angular momentum to the envelope until breakup velocity is reached. After ejection of the envelope, the remnant would consist of a close-binary system containing the hot core of the red giant and the main-sequence companion, surrounded by an expanding planetary nebula that would be ionized by radiation from the hot star. Following dissipation of the nebula and contraction of the core to a white-dwarf configuration, the system would closely resemble V471 Tau. Further decay of the orbit through gravitational radiation would ultimately lead to mass transfer and cataclysmic activity.

Some observational support for these ideas has come from the discovery that UU Sge, the central star of the planetary nebula Abell 63, is a detached eclipsing binary with an orbital period of 11.2 hr (Bond 1976; Miller, Krzeminski, and Preidhorsky 1976; Bond, Liller, and Mannery 1978). However, the period of UU Sge is still sufficiently long that the time scale for gravitational radiation to initiate mass transfer is $\sim 10^{10}$ yr. In order for close-binary planetary nuclei to serve as the progenitors of the cataclysmic variables observed at the present epoch, either angular-momentum losses must occur at a rate greater than provided by gravitational radiation (e.g., Eggleton 1976), or binary central stars with still shorter orbital periods must occasionally be formed.

In this paper, we report our discovery that the nucleus of the planetary nebula Abell 41 is a close binary with a period so short that it must become a

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cataclysmic variable in less than 2×10^9 yr. This discovery provides very strong support for the general scenario outlined above.

II. OBSERVATIONS

UU Sge contains a sdO primary and a red-dwarf companion with a strongly heated hemisphere; because of the large reflection effect, a system like UU Sge would exhibit detectable light variations even if its orbit were not sufficiently inclined for actual eclipses. Therefore, in considering the most efficient method to use in a search for further close-binary central stars, we concluded that photometric monitoring would be most suitable, and we have undertaken a large-scale photometric survey of the central stars of selected planetary nebulae. All of our survey work to date has been carried out with high-speed photometers on 0.9-m reflectors at Kitt Peak National Observatory (KPNO), Cerro Tololo Inter-American Observatory (CTIO), and Louisiana State University (LSU) Observatory. At KPNO and LSU we have used the two-star photometers and reduction techniques described by Grauer and Bond (1981), while at CTIO we have used a conventional single-channel photometer.

In selecting central stars for photometric monitoring, we have given highest priority to objects already suspected of variability by other workers, and to central stars of low-surface-brightness nebulae (for the purely observational reason that there is less contamination by nebular background light for such objects). Thus one of the objects we chose was the 15th magnitude central star of the planetary nebula Abell 41, a nebula discovered by Abell (1966) during his search for faint planetaries on plates of the Palomar Sky Survey, and suspected by him of having a variable central star. The 1950 coordinates of the central star are $17^h26^m10^s$, $-15°10'.8$.

All of our photometric measurements were made differentially with respect to a comparison star (BD $-15°4566$) lying $34^s.2$ east and 44″ north of the central star. For the observations made at KPNO and LSU with two-star photometers, the comparison star was monitored simultaneously with the central star, and division by the comparison observations was used to remove effects of atmospheric transparency variations (which never exceeded a few percent on the nights used) and of atmospheric extinction. Conventional single-channel techniques were used at CTIO on photometric nights only. Standard filters of the *UBV* system were used at all three telescopes. Measurements of the comparison star on seven nights at KPNO and CTIO relative to *UBV* standards showed it to be constant and gave $V = 10.01$, $B-V = 0.57$, and $U-B = 0.09$.

High-speed photometry of the central star of Abell 41 obtained by us in 1981 at KPNO, CTIO, and LSU established that the object is a rapid variable. However, none of the photometric runs were sufficiently long to reveal the character of the light variations.

An intensive series of photometric runs made by A. D. G. in 1982 April and May at KPNO and CTIO, respectively, revealed that the variations are strictly periodic. Figure 1 shows our longest photometric run, obtained with a *B* filter at CTIO on 1982 May 28 (UT). The light curve shows broad 0.15-mag minima recurring at intervals of 2^h43^m. True eclipses do not appear to occur.

Timings were determined for all well-observed minima using a simple graphical method, and are listed in Table 1. A least-squares fit to these times of minimum (giving half-weight to the first two, which are of lower

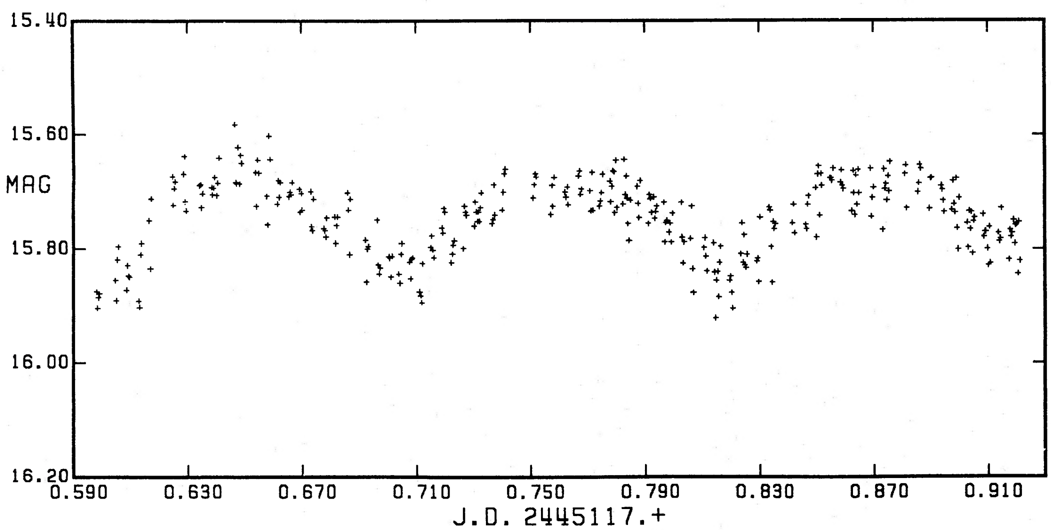

FIG. 1.—*B* light curve for the central star of Abell 41 on 1982 May 28, obtained during an 8 hr observing run with the 0.9 m reflector at CTIO. The original 5 s integrations have been summed into 30 s bins, and the resulting *B* magnitudes are plotted against heliocentric Julian Date. Minima are seen to recur at 2^h43^m intervals.

TABLE 1

TIMES OF MINIMUM FOR ABELL 41

HJD	E	$O-C$	Telescope and Observer
2444703.9734	−3347	−0.0024	KPNO 0.9 m, A. D. G.
4705.9029	−3330	+0.0022	CTIO 0.9 m, H. E. B.
5082.9480	0	+0.0017	KPNO 0.9 m, A. D. G.
5084.8715	17	+0.0004	KPNO 0.9 m, A. D. G.
5087.9277	44	−0.0006	KPNO 0.9 m, A. D. G.
5115.6691	289	+0.0002	CTIO 0.9 m, A. D. G.
5115.7829	290	+0.0008	CTIO 0.9 m, A. D. G.
5117.7061	307	−0.0008	CTIO 0.9 m, A. D. G.
5117.8197	308	−0.0005	CTIO 0.9 m, A. D. G.
5118.7249	316	−0.0011	CTIO 0.9 m, A. D. G.

NOTE.—E = cycle count; $O-C$ = observed time of minimum minus calculated time of minimum from the ephemeris given in the text.

observational quality than the others but provide a considerable increase in time baseline) yields the ephemeris

$$\text{HJD (min)} = 2{,}445{,}082.9463 + 0.1132269E\,.$$
$$\pm 3 \qquad\qquad \pm 3$$

We have noted no evidence for mass transfer in this close binary system (such as flickering activity or changes in brightness level from night to night). We will therefore assume in the following discussion that the system is a detached binary.

Figures 2 and 3 show mean light curves derived from our observations. Figure 2 shows the B light curve obtained at KPNO; we have binned the original 9688 5 s integrations obtained over seven nights in 1982 April into 200 equally spaced phase bins, using the ephemeris given above. The light level is slightly different from that of Figure 1, because of the different filter sets and diaphragm sizes used at CTIO and KPNO, leading to slightly different amounts of nebular background. Figure 3 shows the U light curve obtained at CTIO on 1982 May 26; in this case, 2509 5 s integrations have been sorted into 100 phase bins. The B and U light curves are essentially identical. Both reveal shallow minima and a flat-topped maximum.

On three nights at CTIO we obtained scattered UBV observations. These data are insufficient to reveal a useful V light curve or any changes in color with phase, but do show a mean magnitude and colors of $V = 15.6$, $B-V = 0.19$, and $U-B = -1.14$; these values may be slightly affected by the nebular background.

III. PARAMETERS OF THE BINARY SYSTEM

a) The Orbital Period

It is not immediately clear whether the orbital period of the central star of Abell 41 is 2^h43^m (with one minimum per orbit, as assumed in Figs. 2 and 3) or 5^h26^m (with two minima per orbit).

If the longer period is the correct one, our data show that the two halves of the light curve (phases 0.0–0.5 and 0.5–1.0) are essentially identical, so that the variations must be dominated by ellipticity of the primary star, with no significant reflection from the secondary. However, the light curves have a distinctly flat-topped appearance instead of the nearly sinusoidal variation that would be produced by ellipticity.

For the 2^h43^m period, the light variations are dominated by heating of the secondary star by radiation from the very hot primary, and the system (aside from the much shorter period) would be very similar to UU

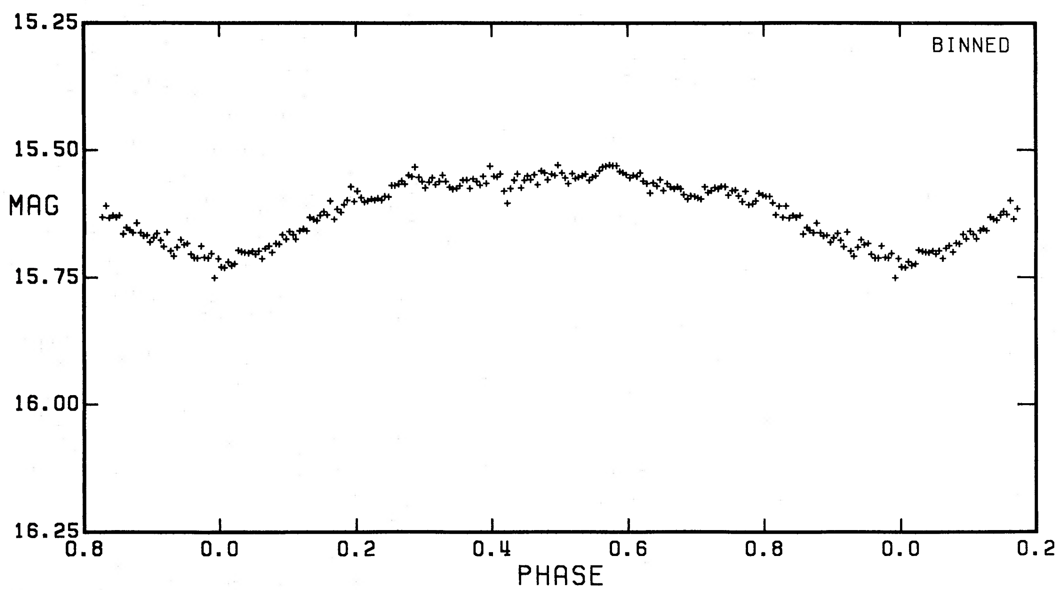

FIG. 2.—Mean B light curve of Abell 41, obtained with a 0.9 m reflector at KPNO on seven nights in 1982 April with the University of Arkansas at Little Rock two-star photometer. A total of 9688 5 s integrations have been binned into 200 equally spaced phase intervals, using the ephemeris given in the text.

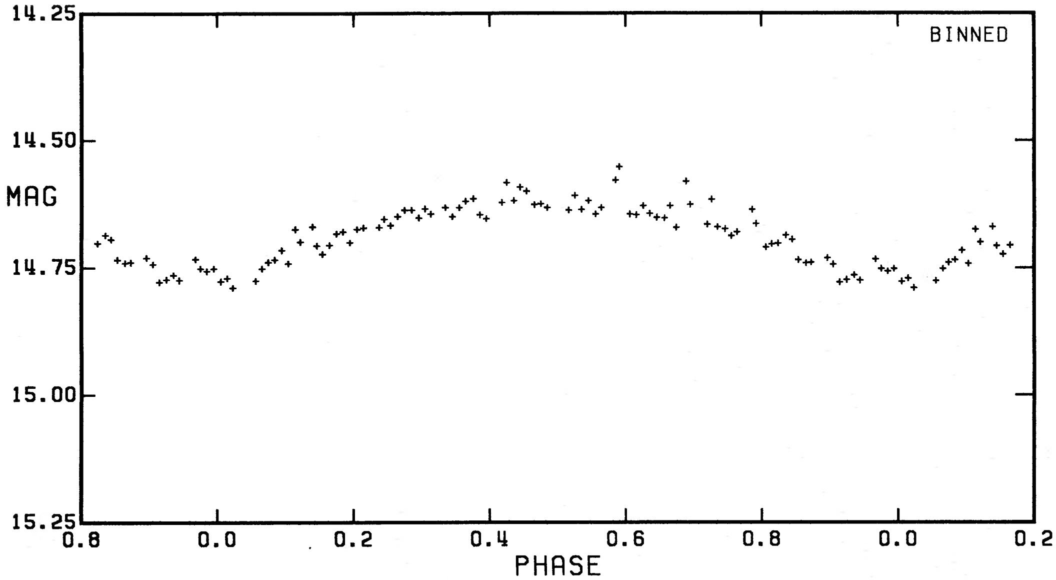

FIG. 3.—Mean U light curve of Abell 41, obtained at CTIO on 1982 May 26. Here 2509 5 s integrations have been binned into 100 equally spaced phase intervals.

Sge. Furthermore, a combination of reflection and ellipticity can readily produce the shape of the light curve that is observed.

In the remainder of this paper, we will assume that the orbital period is 2^h43^m. It should be possible to settle the period question unambiguously with radial-velocity observations, since the spectrum of the primary shows a weak He II λ4686 absorption line (J. Liebert and R. Green, private communication).

b) *Distance*

Cahn and Kaler (1971) have estimated a distance to Abell 41 of 4.5 kpc, on the basis of an assumed nebular mass, Abell's (1966) photographic surface brightness, and interstellar extinction derived from a model of the galactic dust distribution. The estimate is obviously rather uncertain.

An alternative method is to use our colors of the central star to estimate the color excess, and then use a color-excess/distance relation to obtain the distance. The primary star must be extremely hot in order to excite the nebula, and should have $B-V \approx -0.35$. Our observed $B-V$ therefore indicates $E(B-V) \approx 0.55$. The study of Lucke (1978) indicates a color excess of $\sim$0.6 mag kpc^{-1} in the direction of Abell 41, leading to a distance estimate of $\sim$1 kpc.

In the discussion below, we will assume distances of 4, 2, and 1 kpc. The corresponding visual absolute magnitudes of the central star (for an apparent magnitude of 15.6 and a color excess of 0.55) are +1.0, +2.5, and +4.0.

c) *Properties of the Stars*

Upper limits to the mass and radius of the secondary star follow immediately from Paczyński (1981, eq. [4]) and the observational conclusion that the secondary does not fill its Roche lobe:

$$8.85 M_2^{-1/2} R_2^{3/2} < P \ .$$

Here and in the following discussion, we express masses and radii in solar units and the orbital period in hours. Assuming further that the secondary obeys the lower-main-sequence relation

$$R_2 = 0.76 M_2^{0.78}$$

(Rappaport, Joss, and Webbink 1982), we find

$$R_2 < 0.31 \quad \text{and} \quad M_2 < 0.32 \ .$$

Although the primary star probably lost its red-giant envelope in a considerably different fashion, its subsequent evolution should not differ greatly from that of a single-star planetary nucleus. We will therefore assume that Schoenberner's (1981) evolutionary tracks apply, and we will follow him in assuming a typical central-star mass of 0.6 $M_\odot$. For $0.05 < M_2 < 0.3$ and $M_1 = 0.6$, the separation of the stars, a, must be $0.90 \pm 0.05\ R_\odot$. The radius of the primary's Roche lobe is $0.47 \pm 0.05\ R_\odot$.

As it evolves down Schoenberner's track, a star of 0.6 $M_\odot$ reaches $M_V = +1.0$, +2.5, and +4.0 at effective temperatures of 69,000, 105,000, and 145,000 K, respectively (Schoenberner 1981, Fig. 7); the corresponding radii are 0.50, 0.20, and 0.08 $R_\odot$.

Let the effective temperatures of the primary star and of the heated hemisphere of the secondary be T_1 and T_2. Then (if all of the intercepted radiation is reradiated with no diffusion to the unilluminated hemisphere)

$$(T_2/T_1)^4 = 0.5(R_1/a)^2 \ ,$$

which gives $T_2 \approx$ 36,000–42,000 K for the range of T_1

and R_1 given above; the secondary suffers an enormous heating because of its very close proximity to the extremely hot primary. The secondary's heated hemisphere is so hot that it will have nearly the same optical colors as the primary star itself; thus we expect little dependence of the light-curve amplitude upon wavelength over the optical band. Our U and B light curves (Figs. 2 and 3) indeed do seem to have nearly identical amplitudes.

A lower limit to the radius of the secondary can be derived from the amplitude of the reflection effect. Space limitations do not permit us to give the details, but an approximate analysis indicates that R_2 must be larger than $\sim 0.1\ R_\odot$ to provide the observed amplitude, even if the orbital inclination is so high that the system just manages to avoid eclipses.

IV. APPEARANCE OF THE NEBULA

Figure 4 (Plate 6) shows the appearance of Abell 41 on a prime-focus plate very kindly obtained for us by W. Herbst with the CTIO 4-m telescope. The central star is surrounded by a roughly elliptical shell, with major and minor axes of 19″ and 13″. The shell shows two obvious, diametrically opposed knots. Possibly these knots represent a roughly toroidal structure ejected in the orbital plane of the binary and seen at a fairly high inclination, while the fainter elliptical shell may represent lower-density material ejected out of the orbital plane, much as predicted recently by Livio (1982).

V. FUTURE EVOLUTION

The foregoing discussion has led to the conclusion that the central star of the planetary nebula Abell 41 is a very close, but detached, binary system; in fact, it is the shortest-period detached binary system known (even if the period is 5^h26^m). The binary components are the hot primary (which excites the nebula) and a secondary of M-dwarf dimensions ($R_2 = 0.1$–$0.3\ R_\odot$). The hemisphere of the secondary that faces the primary is heated to $\sim$40,000 K.

On a time scale of a few times 10^4 yr, the planetary nebula will dissipate, and the primary star will complete its contraction to white-dwarf dimensions. Then a long interval of inactivity will ensue, but the M dwarf must eventually be brought into contact with its Roche lobe because of loss of energy from the system by gravitational radiation.

The rate of period change due to gravitational radiation, assuming masses of 0.6 and $0.2 \pm 0.1\ M_\odot$ and a period of 2^h43^m, is $dP/dt = -(1.1 \pm 0.5) \times 10^{-13}$ (see Kraft, Mathews, and Greenstein 1962). This rate would lead to a detectable phase shift in the time of minimum of $0\overset{d}{.}001$ in 100–175 yr, so we urge future observers to obtain timings.

With the above rate of orbital decay, a $0.2\ M_\odot$ secondary will begin to overflow its Roche lobe after 6×10^8 yr (at which time the orbital period will be 2.0 hr), thus forming a cataclysmic binary. If $M_2 = 0.1\ M_\odot$, mass transfer will begin after 1.8×10^9 yr, at an orbital period of 1.3 hr. If M_2 is near $0.3\ M_\odot$, cataclysmic activity is now on the verge of beginning.

It may be significant that Abell 41 will first appear as a cataclysmic variable with a period near 2 hr, since there are numerous cataclysmic binaries known with periods of 1.3–2 hr, but very few with periods of 2–3 hr. At least part of the reason for this well-known period gap may be that a large fraction of ultra-short-period binaries do not begin to transfer mass until after they have passed through the period gap.

The discovery of the binary nature of the central star of Abell 41—an object that must inevitably initiate nova-like behavior in the astronomically near future—provides compelling evidence that cataclysmic variables are the descendants of wider binaries that have disposed of orbital angular momentum by ejecting a planetary nebula.

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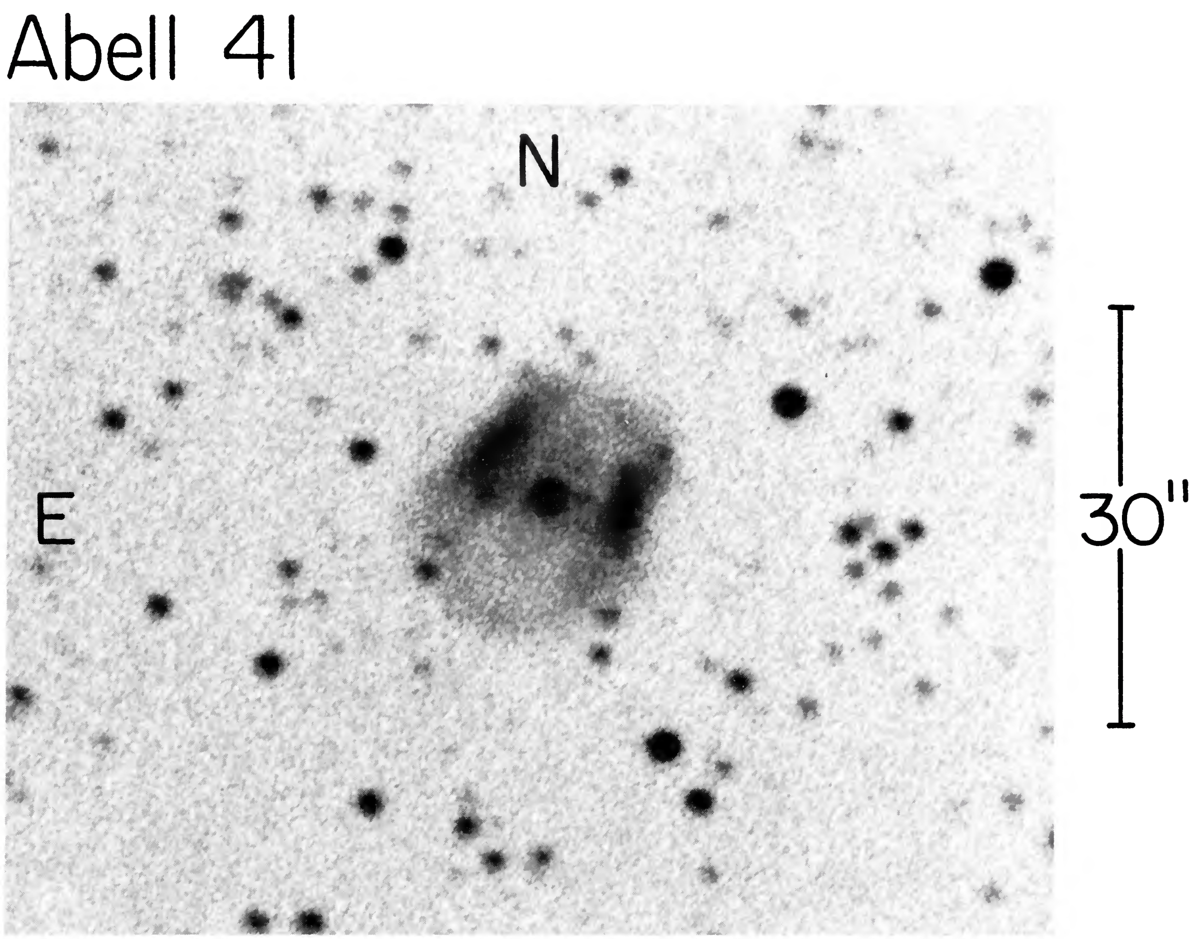

FIG. 4.—Direct photograph of Abell 41, obtained with the CTIO 4 m prime-focus camera. The exposure was 10 min on IIIa-F emulsion behind a GG-495 filter.

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