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S-154 IN THE LARGE MAGELLANIC CLOUD: SPECTRAL EVOLUTION FROM A LUMINOUS Fe II VARIABLE TO A SYMBIOTIC-LIKE STAR

R. A. REMILLARD,[1,2] E. ROSENTHAL,[3] I. R. TUOHY,[2,4] D. A. SCHWARTZ,[5]
D. A. H. BUCKLEY,[6] AND R. J. V. BRISSENDEN[5]

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ABSTRACT

The emission-line star, S-154, is a luminous variable in the Large Magellanic Cloud. Between 1988 February and December, S-154 changed its spectral appearance from a low-excitation "Fe II star" into a high-excitation state that resembles symbiotic stars. Before the transition (1984–1988), the spectral features had been primarily confined to emission lines of H and Fe II; afterward, we observed emission from He I, He II, O III, and the λ6830 band. This transition is reminiscent of spectral variations observed in RX Puppis, but the spectrum of S-154 out to 1 μm shows no evidence of the Mira variable contained in that symbiotic star. The simplest interpretation for the spectral evolution of S-154 is the optical thinning of the nebula. This study implies that spectral type of the central star(s) does not always dominate the physical conditions in the circumstellar material and thereby determine the nebular classification. The membership of S-154 in the LMC was confirmed with a radial velocity measurement of +274 km s^{-1}, enabling the measurement of absolute luminosity. The historical light curve (1880–1990) obtained from 346 photographic plates of the Harvard Plate Library exhibits ~4 mag of variations, with a range of $-6 < M_B < -2$. There is no evidence of coherent modulations that would represent the orbital period of a symbiotic binary. We originally investigated S-154 as an optical candidate of a *HEAO 1* X-ray source on grounds of positional coincidence. However, efforts to confirm the X-ray emission with *EXOSAT* were negative, and the status of S-154 as an X-ray source remains unclear.

Subject headings: Magellanic Clouds — stars: individual (S-154) — stars: variables: others

1. INTRODUCTION

Several years ago, we encountered an unusual UV object while working to identify optically 1H 0451−747, one of the X-ray sources from the *HEAO 1* survey (Wood et al. 1984). The optical spectrum exhibited a flat continuum with emission lines that included multiplets of Fe II and an extremely strong Hα line. We soon realized that the object had been cataloged by Henize (1956) as "S-154" in a survey of LMC stars with Hα emission. To our knowledge, there have been no further publications on this object, probably because S-154 is located in the outer region of the LMC, and Henize observed the star in a faint state. Our observations with the coudé spectrograph on the 74 inch (1.9 m) telescope at Mount Stromlo Observatory in 1984 May produced a radial velocity measurement (at Hα) of 274 km s^{-1}, confirming membership in the LMC. A finding chart for S-154 is provided in Figure 1, and the celestial position is given in the caption.

There were no other optical candidates for the X-ray source identification; however, since the star is so peculiar, we sought a confirmation of the X-ray emission using the imaging capabilities of the *EXOSAT Observatory*. The observation (1984 October) with the imaging LE detector (0.1–2.0 keV) produced a blank field, with a 3 σ upper limit of 0.008 LE counts s^{-1} with the thin Lexan filter. This corresponds to a flux < 1 mCrab for an intrinsic absorption of $N_H < 10^{22}$ cm^{-2}. Neither was there a source detection in the ME instrument, with a 3 σ upper limit of 0.4 mCrab at 1–7 keV. This is clearly less than the source measured with *HEAO 1* (1.5 mCrab at 1–20 keV). The only available conclusions are (1) the *HEAO 1* detection appears to be a transient X-ray source, and (2) there is no persistent, strong X-ray emission from S-154. Interest in the optical properties and the nature of this object motivated further study.

There are several types of luminous stars that exhibit optical Fe II emission, including some peculiar objects in the Galaxy (e.g., Downes 1984), VV Cep stars (Cowley 1969), some symbiotic stars (e.g., Rossi et al. 1988), and the "luminous blue variables" (LBVs) such as η Car and related stars in neighboring galaxies (e.g., Humphreys 1975). Such objects are generally envisioned as luminous stars immersed in nebulae, which may arise either from accretion in a binary system or from massive stellar winds, especially in the case of LBVs or symbiotics that contain Mira variables. However, the nebular classifications are only partially understood, and the nature of the embedded stars may be a complete mystery when the spectrum is void of superimposed absorption lines, as in the case of S-154.

As we will document below, an important turn of events occurred during 1988 when the spectrum of S-154 changed dramatically. Emission lines of high excitation appeared in the spectrum, including lines of He II, N III, and O III. The latter display distinctly resembles symbiotic stars. The spectral evolution of the circumstellar material in S-154 provides new clues

[1] Center for Space Research, M.I.T., 77 Massachusetts Avenue, Cambridge, MA 02139.
[2] Guest Observer, Cerro Tololo Inter-American Observatory, which is operated by AURA, Inc. under contract with the National Science Foundation.
[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
[4] British Aerospace Australia Ltd., P.O. Box 180, Salisbury SA 5108, Australia.
[5] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[6] South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa.

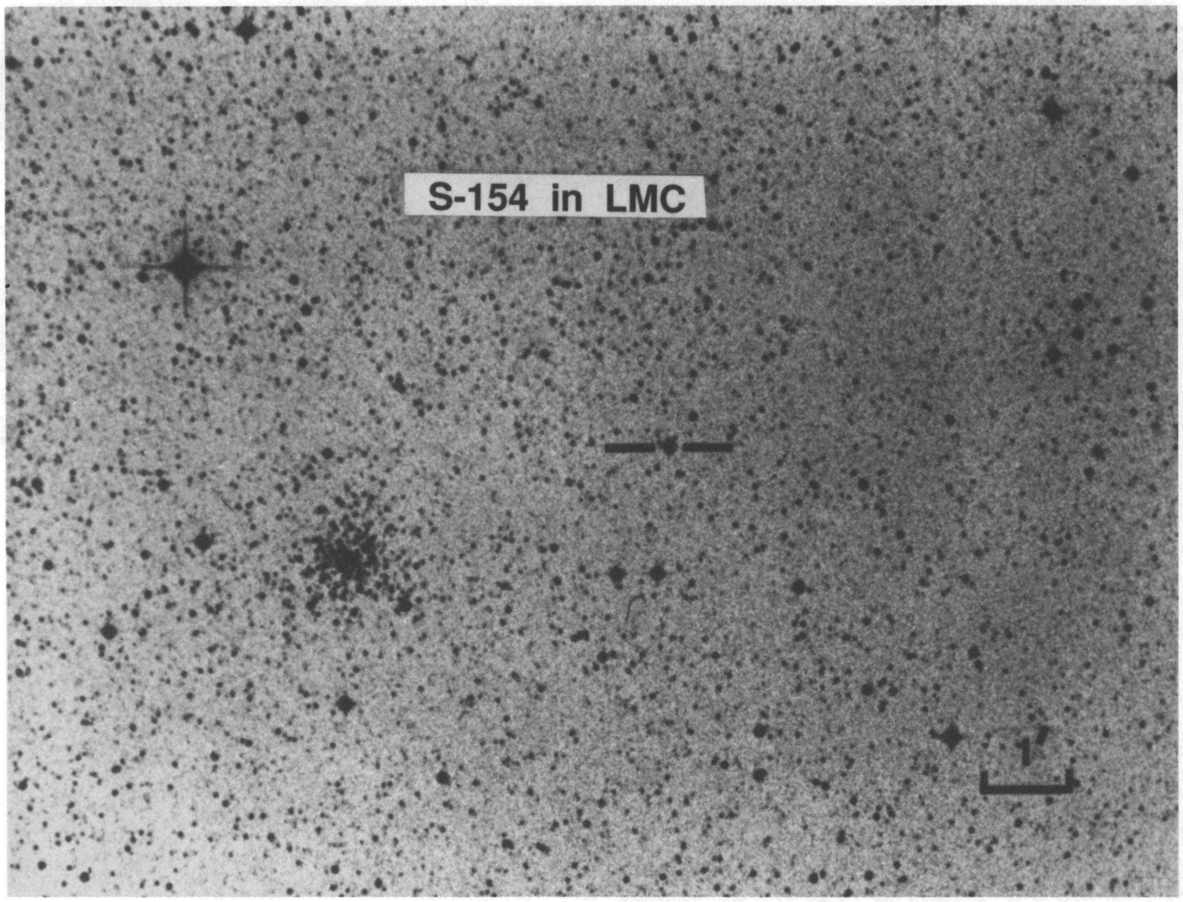

FIG. 1.—A finding chart for S-154, photographed from the J print of the SRC Sky Survey. North is toward the top, and east is to the left. The coordinates are (epoch 1950; ±2″) $\alpha = 04^h53^m17^s.0$, $\delta = -75°08'27''$.

regarding the relation between symbiotic stars and other types of luminous nebulae.

2. OPTICAL SPECTROSCOPY OF S-154

A journal of optical observations is given in Table 1. Spectral observations during 1984 and 1986 were made with the 3.9 m Anglo-Australian telescope (AAT) at Siding Spring Observatory. The data were obtained with the RGO spectrograph and IPCS detector, a two-dimensional photon-counting instrument operated with ~10 Å resolution. During 1986, we additionally used the Faint Object Red Spectrograph (FORS), a CCD detector operated with 20 Å resolution. The IPCS/FORS double spectrograph used a dichroic filter that splits the incoming beam at 5500 Å. Observations during 1988 December were made with the 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO), using the 2-D Frutti spectrograph operated with 10 Å resolution. On two other occasions spectra were obtained with the Dual Beam Spectrograph (DBS) on the 2.3 m telescope of the Australian National University at Siding Spring Observatory. The latter instrument also uses a dichroic filter, and microchannel plates are used to count photons in the dispersed light from each beam. The spectral reductions included standard procedures at each observatory to calibrate the wavelength and flux density.

The spectrum of S-154 on 1984 February 9 is shown in Figure 2. As is typical for this object, the Hα line is the dominant feature, and the Balmer decrement is steep. In Figure 3 we show spectra at seven epochs, with the Hα lines truncated in order to view the remaining spectral features. The Hα/Hβ flux ratio is reported in Table 1. The first five spectra are generally similar, showing emission lines of low excitation and a Balmer jump in absorption that increases with time. Weaker features are evident at wavelengths of Fe II emission, including λ4491, λ4515, λ4576, λ5169, λ5198, λ5234, λ5317, λ5363, and λ5535 Å (Meinel, Aveni, & Stockton 1975). There also appear to be [Fe III] at λ5270 and weak O I at λ6300.

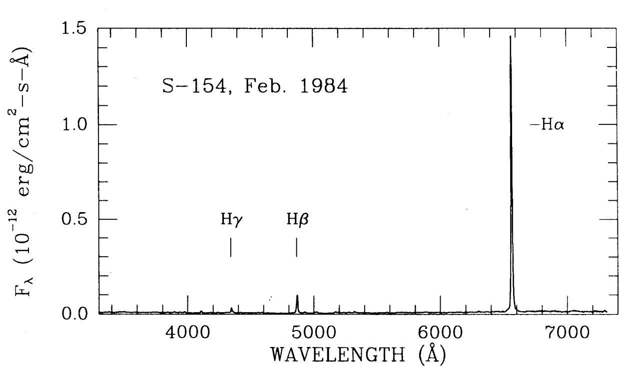

FIG. 2.—Optical spectrum of S-154 during 1984 February. The emission line at Hα is a dominant feature of S-154 during every spectral observation listed in Table 1.

TABLE 1

JOURNAL OF OBSERVATIONS

A. SPECTROSCOPY

Date (UT)	Telescope	Instrument	Hα/Hβ
1984 Feb 9.60	AAT	IPCS	17.0
1984 Oct 19.75	AAT	IPCS	7.7
1986 Feb 7.61	AAT	IPCS + FORS	3.0
1986 Jul 27.81	AAT	IPCS + FORS	3.7
1988 Feb 21.53	ANU 2.3 m	Dual beam spectrograph	5.8
1988 Dec 16.35	CTIO 4 m	2-D Frutti	5.8
1989 Feb 8.55	ANU 2.3 m	Dual beam spectrograph	2.6

B. PHOTOMETRY OF S-154[a]

Date (UT)	Telescope	Instrument	Star	V	$U-B$	$B-V$	$V-R$	$V-I$
1986 Feb 11	ANU 1.0 m	TCC	S-154	13.90	−0.24	+0.45	+0.62	+1.16
1987 Apr 28	CTIO 1.0 m	CFCCD	S-154	15.21	...	+0.13	...	−0.08
1989 Nov 8–13	CTIO 1.5 m	CFCCD	S-154	15.30	−0.77	+0.16	+1.65	+1.25

C. PHOTOMETRY OF LOCAL REFERENCE STARS[b]

Date (UT)	Telescope	Instrument	Star	V	$U-B$	$B-V$	$V-R$	$V-I$
1989 Nov 8–13	CTIO 1.5 m	CFCCD	Star A	14.33	+0.18	+0.77	+0.44	+0.88
	CTIO 1.5 m	CFCCD	Star B	14.30	+0.60	+0.98	+0.58	+1.14

[a] Uncertainties are ±0.02 mag for 1986 and 1987 observations. The 1989 measurements have errors of ±0.015 mag, except for the $U-B$ value which has an uncertainty of ±0.03.

[b] Reference star "A" is 1.'5 SSE of S-154, and star "B" is 0.'5 due east of star A (see Fig. 1).

There is a dramatic transition to emission lines of higher excitation that occurs between 1988 February and December. The two lower spectra in Figure 3 resemble that of symbiotic stars, with emission lines that include He II λ4686, He I lines (λ4026, λ4388, λ4472, λ5876, λ6678, λ7065, and λ7281), the C III/N III band at λ4640, weak [O III] (λ4959 and λ5007), continued Fe II emission, and the broad feature at λ6830, a spectral hallmark of the symbiotic class (Blair et al. 1983; Kenyon 1986; Schmid 1989).

A technical classification of S-154 as a symbiotic star is prevented by the lack of absorption lines that signify an underlying late-type supergiant (Kenyon 1986). In the case of S-154, the circumstellar nebula may be unusually bright compared to typical symbiotic stars, or the primary star may be shrouded in dust, as in the case of the Mira variable in RX Puppis (Allen & Wright 1988). The AAT/FORS spectra extend to 1 μm, and in Figure 4 we show the 1986 July spectrum of S-154 along with a M7 III star for comparison. To first order, the atmospheric absorption features in S-154 were removed via observations of HD 26169 and HD 33771. There are no signs of continuum modulations attributable to a late-M giant; the significant features are confined to emission lines at Hα, O I (λ8446), and Ca II (λ8498, λ8542, and λ8662).

3. OPTICAL PHOTOMETRY OF S-154

Photometric measurements of S-154 and two local reference stars are reported in Table 1. The 1986 observations were made with the 1.0 m telescope of the Australian National University at Siding Spring Observatory. These data were obtained with the two-channel chopping photometer (TCC), which contains photomultiplier tubes that alternately sample the object and the sky background. The aperture was 20″, and the objects were centered with the assistance of a TV camera that was used to view the sky through the aperture before and after each sequence of measurements. Photometry during 1987 and 1989 were performed with the Cassegrain Focus CCD (CFCCD) instrument on the 1.0 and 1.5 m telescopes at CTIO. Data reductions used a 10″ synthetic aperture, and the magnitude calibrations were made by observing standard stars of Landolt (1983).

The photometric results indicate substantial brightness and color variations that reflect some of the spectral changes displayed in Figure 3. The $U-B$ and $B-V$ indices are sensitive to the strong variations in the high-order Balmer lines and the Balmer continuum while variable Hα emission and near-IR excess causes considerable movement in the $V-R$ and $R-I$ indices.

4. HISTORICAL RECORD FROM THE HARVARD PLATE LIBRARY

A photographic light curve for S-154 was obtained using the resources of the Harvard plate library (Rosenthal 1985). The study was conducted by comparing the brightness of S-154 against 12 field stars that were later calibrated from CCD photometry during the 1989 November observations at CTIO. Meaningful results were derived from 346 deep plates obtained between 1880 and 1990; all of these were primarily sensitive in the optical B band. With a visual magnitude, $V \sim 14.5$, the LMC distance modulus implies an absolute magnitude, $M_V \sim -4$, placing it at the lower boundary of the luminosity realm of the supergiants. The photographic comparisons revealed about 4 mag of variability, ($-2 > M_B > -6$), and the results are shown in Figure 5. Examples of high and low states of optical brightness are shown in Figure 6. Large amplitude variations are also seen among symbiotic stars (Kenyon 1986), and these may include both faint states and prolonged outbursts.

The photographic light curve was searched for periodic modulations by computing the Θ-statistic of Stellingwerf (1978) for trial periods between 1.0 and 4×10^4 days. This

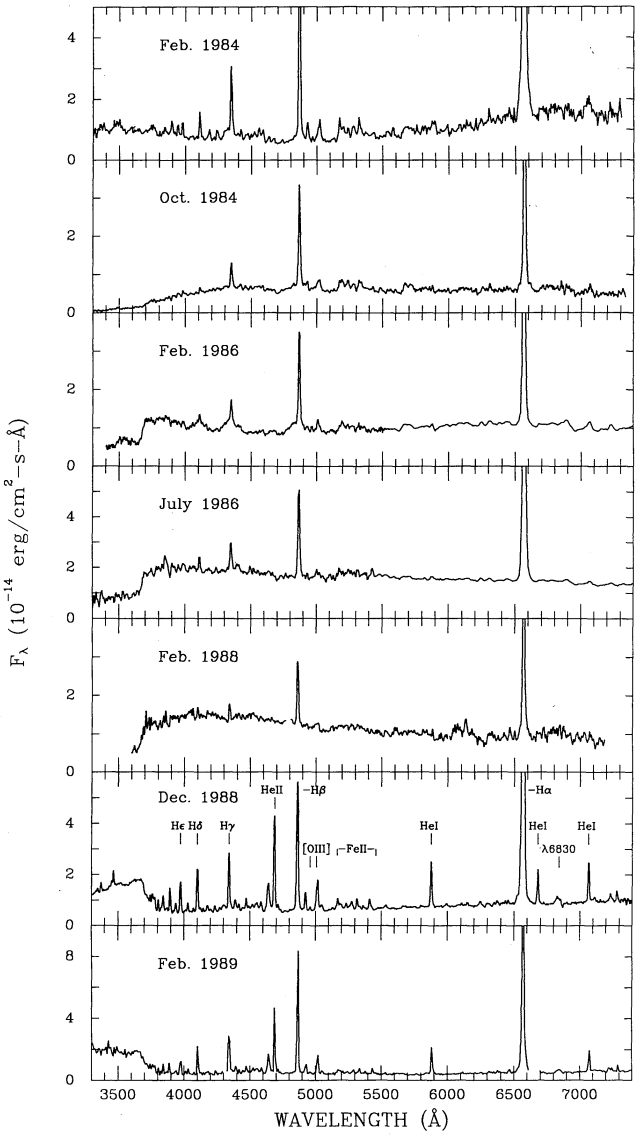

FIG. 3.—Sequence of optical spectra of S-154, with the Hα line truncated in order to view the other emission features. Selected emission lines are marked in the panel for 1988 December. The excitation level of the emission lines increased dramatically between 1988 February and December, exhibiting a transition to a spectrum that resembles symbiotic stars.

method folds the light curve into "phase bins" and computes the bin-averaged variance (Θ), normalized by the overall data variance, for each trial period. There is a highly significant result ($\Theta = 0.32$) at a period of 10,109 days (27.68 yr). However, it appears that this result is an artefact of data sampling, since the data window function contains considerable power at this timescale. The folded light curve exhibits the full ~4 mag amplitude of the historical light curve with maxima related to the bright points near 1946 and minima in phase with the low values near 1905. A strict interpretation of this period is apparently ruled out by the absence of a deep minimum near 1987–1989, as demonstrated by the CCD photometry given in Table 1.

Other less significant dips in the Θ-statistic are observed at periods ~360, 29.6, and 27.3 days (and multiples thereof). The latter results are also sampling artefacts associated with annual

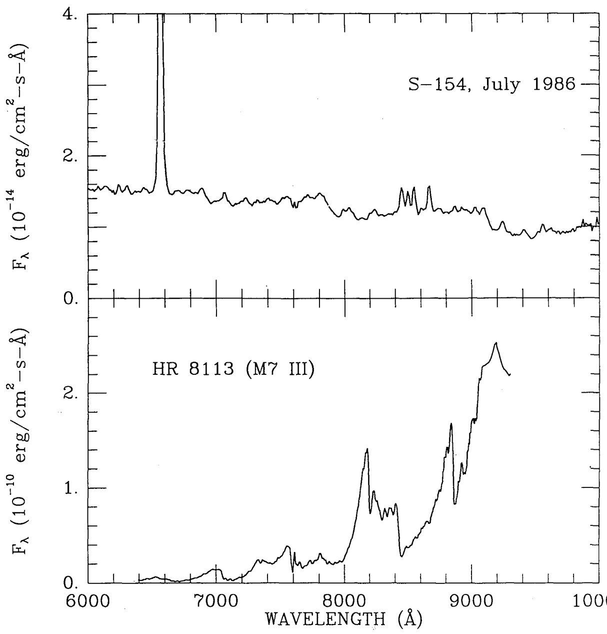

FIG. 4.—Red spectrum of S-154 compared with that of a late M giant. There is no sign of an embedded late-type giant or Mira variable in the optical spectrum out to 1 μm.

and monthly observing patterns, and there are corresponding dips in the Θ-statistic computed for the data window function at these times scales. We conclude that the primary variations are aperiodic outbursts, another characteristic related to the symbiotic class (see Kenyon 1986).

5. DISCUSSION

While it seems clear that S-154 contains a luminous, embedded star, the type of star(s) and the origin of the nebula remain unknown. The low-excitation spectra and the lack of absorption bands out to 1 μm resemble LBV stars such as η Car (see also "LMC-anonymous"; Michalitsianos, Kafatos, & Shore 1989a. While S-154 is 3–4 mag fainter than early supergiants and LBV in the LMC (e.g., Stahl et al. 1983), it is

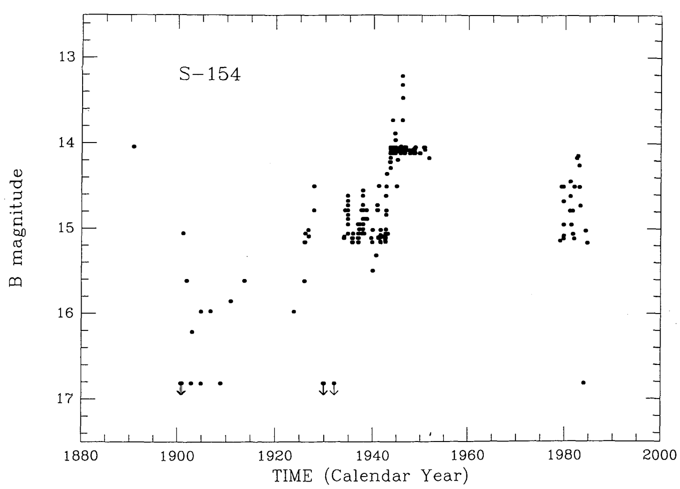

FIG. 5.—Photographic light curve constructed from the Harvard Plate Library. The blue magnitudes were calibrated with CCD photometry of 12 local comparison stars.

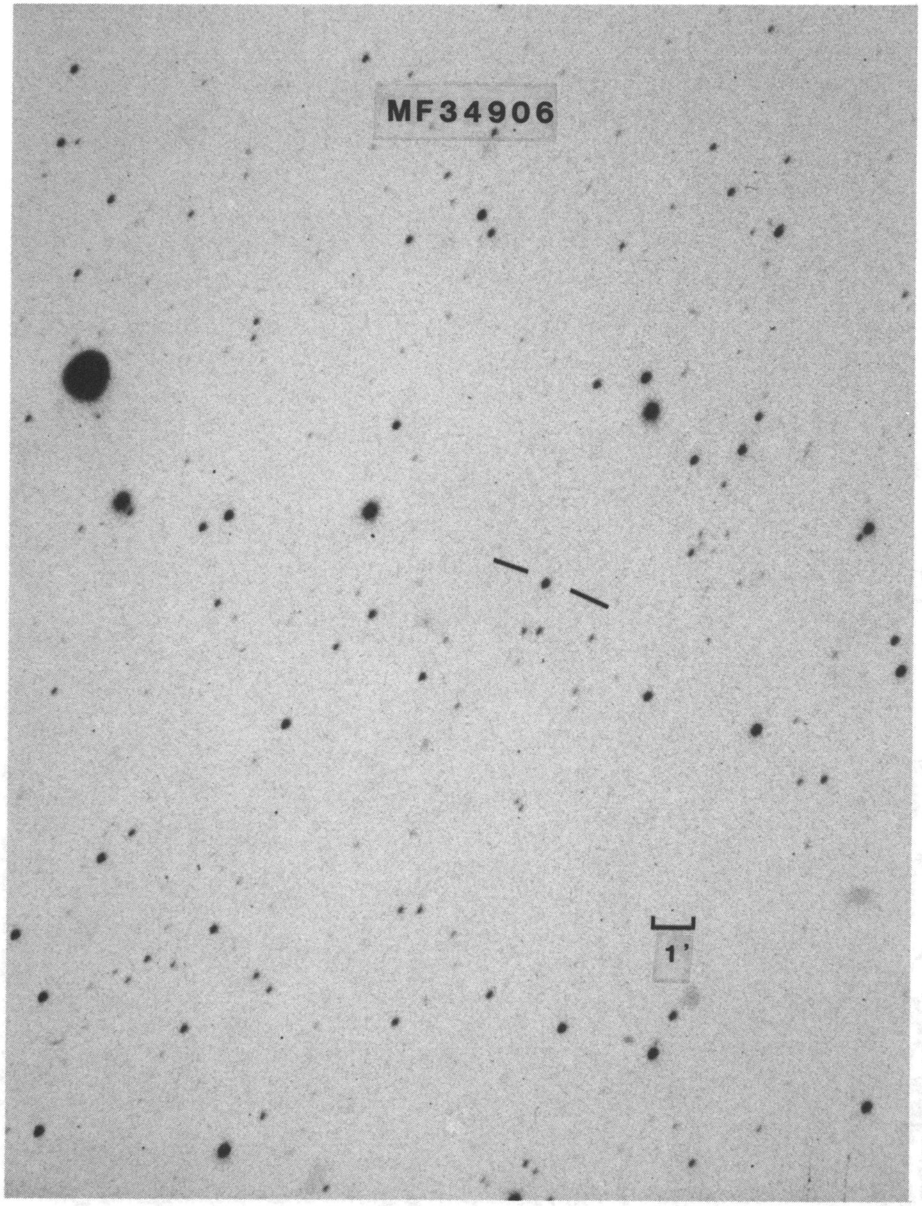

FIG. 6a

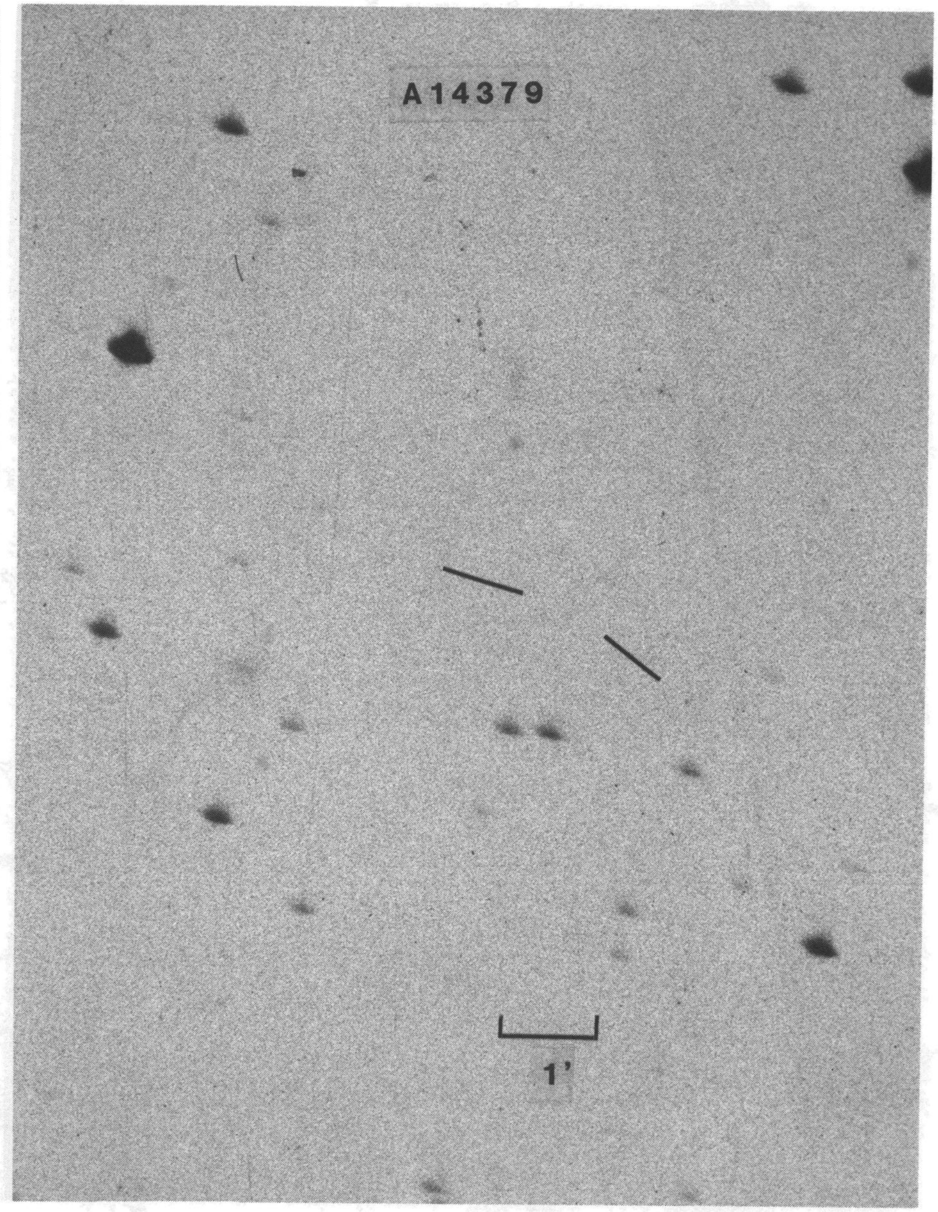

FIG. 6b

FIG. 6.—Two photographs representing bright and faint states of S-154. The left panel (Fig. 6a) shows plate MF 34906, an exposure obtained on 1945 November 4, while the right panel (Fig. 6b) is plate A14379, taken on 1929 November 30. The respective estimated magnitudes are $m_B \sim 13.2$ and $m_B > 16.8$.

possible that the thick nebula diverts substantial optical luminosity to longer wavelengths. On the other hand, the high-excitation spectra of S-154 strongly resemble symbiotic stars. The Mira symbiotic, RX Puppis (Feast, Robertson, & Catchpole 1977), has exhibited a low-excitation state (Klutz & Swings 1981). However, there are important differences between S-154 and RX Puppis; the apparent luminosity (i.e., uncorrected for reddening) and UV continuum are much stronger in S-154, while the Mira star is clearly evident in RX Puppis in the wavelength range of 0.8–1.0 μm (see Allen & Wright 1988).

The spectral evolution of S-154 suggests that the nebular material was relatively cool and dense during the times preceding 1988 December, producing low-excitation lines of H and Fe II (see Netzer & Wills 1983). The Balmer decrement is very steep, but the persistence of a generally flat continuum that extends into the UV suggests that the H emission ratios are primarily modified by optical depth effects rather than by reddening in the circumstellar material. Within a time scale of 10 months or less, the spectrum of S-154 exhibited a transition to the state of high excitation. Several emission lines were observed from atoms having ionization potentials of 20–30 eV, the Balmer decrement flattened substantially, a strong Balmer continuum emerged, and [O III] was detected. The latter characteristics suggest changes in the nebular structure that permitted a view of thin, hot filaments or layers that are more directly photoionized by an embedded hot star.

The cause of these changes in the circumstellar nebula can only be speculated. If S-154 is a symbiotic binary or an LBV, it is possible that the spectral transition signifies the cessation of a high rate of mass loss from the primary star (yet unseen). Alternatively, asymmetries in the geometry of a circumbinary nebula might create the appearance of spectral evolution as our line of sight progresses during an orbital period. We note that all of the spectral observations obtained thus far correspond to fairly "average" levels of luminosity; the historical light curve (Fig. 5) provides evidence of outbursts and faint states that are more extreme than the conditions displayed throughout Figure 3.

The value of securing symbiotic identifications in the Magellanic Clouds has often been noted, principally gaining the ability to measure luminosities, since the distances are known. Only five symbiotics in the LMC and SMC have been reported (Morgan & Allen 1988; Walker 1983), and the majority of these have been carbon star components. The addition of UV spectroscopy combined with serious efforts to model the high-excitation spectra of S-154 may constrain the size of the nebula and the size and temperature of the embedded hot star.

The issue of X-ray emission, while no longer the focus of this study, has not been abandoned entirely. One Galactic X-ray transient, GX 1+4, has the optical spectrum of a symbiotic star (see Bradt & McClintock 1983, and references therein). The *ROSAT* survey contains another sensitive measurement of the X-ray flux. Perhaps more significantly, the *ROSAT* data were collected while S-154 was in its symbiotic-like state, while the *EXOSAT* observations occurred while the nebula was relatively cool and dense.

Wendy Roberts measured the optical position and prepared the finding chart. M. Hazen provided expert guidance at the Harvard Plate Library. Joe Patterson offered helpful comments. We thank the staff of the AAT, Mount Stromlo, Siding Spring Observatory, and CTIO for their invaluable assistance. This work was supported in part by NASA grant NAG8-493 and NSF grants AST 86-12572 and INT 82-11357.

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