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R. J. Sopka
Catonsville Community College

G. Herbig
UNIV MARYLAND

Menas Kafatos
Chapman University, kafatos@chapman.edu

A. G. Michalitsianos
NASA, Goddard Space Flight Center

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RADIO AND OPTICAL OBSERVATIONS OF THE R AQUARII JET

R. J. SOPKA
Astronomy Program, University of Maryland; and Catonsville Community College
G. HERBIG
Lick Observatory, University of California
AND
M. KAFATOS[1] AND A. G. MICHALITSIANOS
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center
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ABSTRACT

VLA observations at 6 cm and Lick Observatory optical plates of R Aquarii indicate the existence of a jetlike feature extending 7″–10″ from the central star. A wide field map at 6 cm shows an unresolved compact radio source which lies close to the axis defined by the jet at a distance of ~ 3′ from R Aqr. Episodic mass transfer in this symbiotic variable could explain the erratic outbursts that R Aqr is known to undergo. Formation of an accretion disk and the accompanying radio-optical jet may characterize the observed outbursts in this system.

Subject headings: stars: accretion — stars: circumstellar shells — stars: long-period variables — stars: mass loss — stars: radio radiation

I. INTRODUCTION

R Aquarii is a symbiotic system which contains a Mira variable having a period of 387 days. The system has long been known to be surrounded by a complex emission nebulosity. The outer nebula has the form of two intersecting arcs which extend to about 60″ east and 75″ west of the star. Outward motion of this nebulosity was suspected by Hubble (1940, 1943) and confirmed by Baade (1943, 1944) who estimated from the expansion rate that the nebulosity had been ejected from R Aqr about 600 years earlier. There is also nebulosity much nearer the star, which merges with the image of R Aqr itself even on the best direct plates. This inner nebulosity is variable to some extent in both brightness and structure; it tends to be extended north and south of the star, at right angles to the outer arcs. A new feature of this inner nebulosity appeared between 1970 and 1977, in the form of a brilliant jetlike feature or spike extending approximately 10″ toward position angle ~ 24°.

In a Very Large Array (VLA) program to determine the microwave spectrum and extended structure of R Aqr, a radio counterpart to the optical jet has been detected at 6 cm with an intensity ~ 25% that of the primary source at R Aqr itself. In a wider field 6 cm map, a spatially unresolved source has been detected approximately 3′ from R Aqr and close to the axis defined by the jetlike structure.

[1]On leave of absence from George Mason University, Fairfax, Virginia.

II. OBSERVATIONS

Continuum radio observations were made with a 50 MHz bandwidth in the "C" configuration of the National Radio Astronomy Observatory (NRAO) VLA on 1981 November 5. The 6 cm maps presented here (Figs. 1 and 3) were derived from three separate observations over a 4 hr period to ensure maximum (u, v)-plane coverage. A total of 43 minutes integration time was spent on source at 6 cm. We also mapped the source region at 2 cm and 1.3 cm with integration times comparable with that at 6 cm, but higher system temperatures at these bands only allowed a determination of the flux of the primary source at R Aqr. The instrumentation and performance characteristics of the VLA are described by Thompson *et al.* (1980).

The 6 cm maps shown in the accompanying figures were produced by the Fourier transform and beam-cleaning routines available at the VLA site and the NRAO-Charlottesville computer facility. Figure 1 shows the source centered on R Aqr and clearly indicates an extension at a position angle of ~ 24°. The synthesized beam at this frequency is an elliptical Gaussian of dimensions $5''.7 \times 4''.5$ and a position angle of 8°. We can account for the observed structure by convolving this beam with two separate unresolved components $7''.0 \pm 0''.5$ apart and having a ratio of about 4 to 1 in flux. This morphology is strikingly similar to that seen in the recent near-ultraviolet photograph (Fig. 2, Plate L1) obtained by a direct plate at the Lick Observatory.

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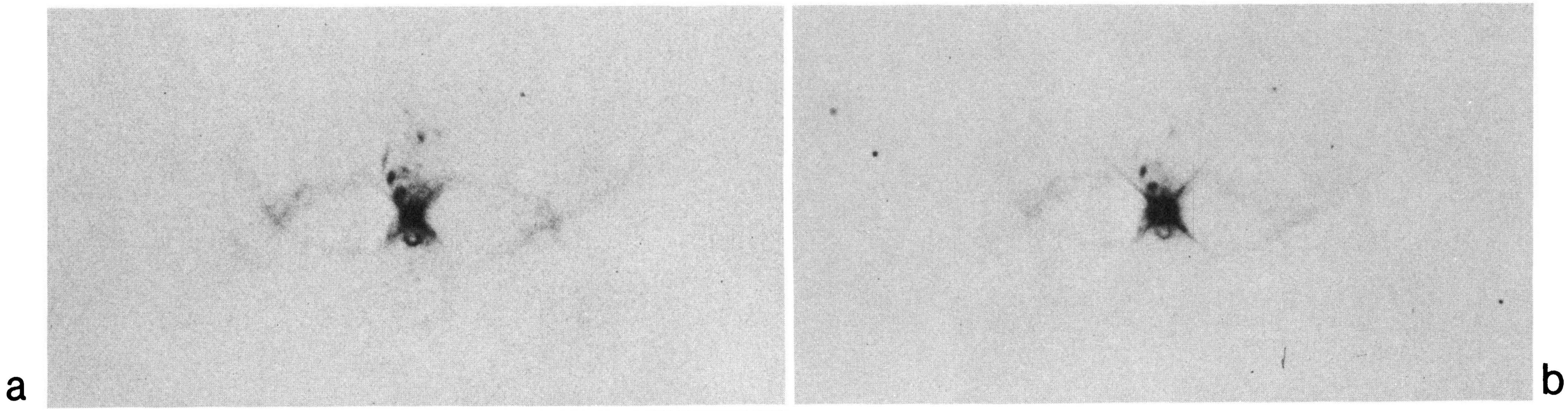


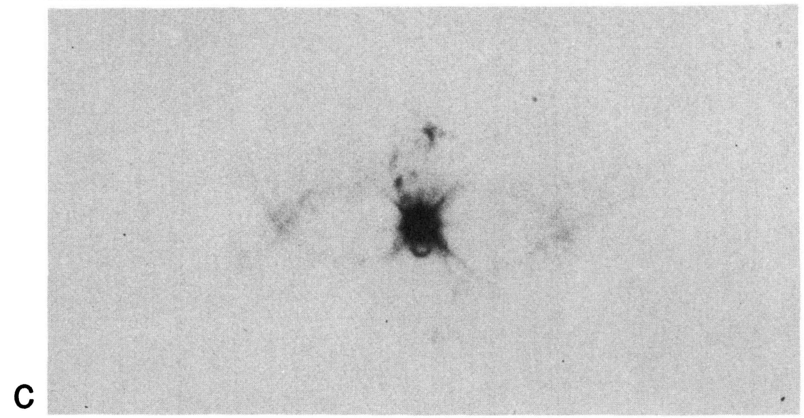
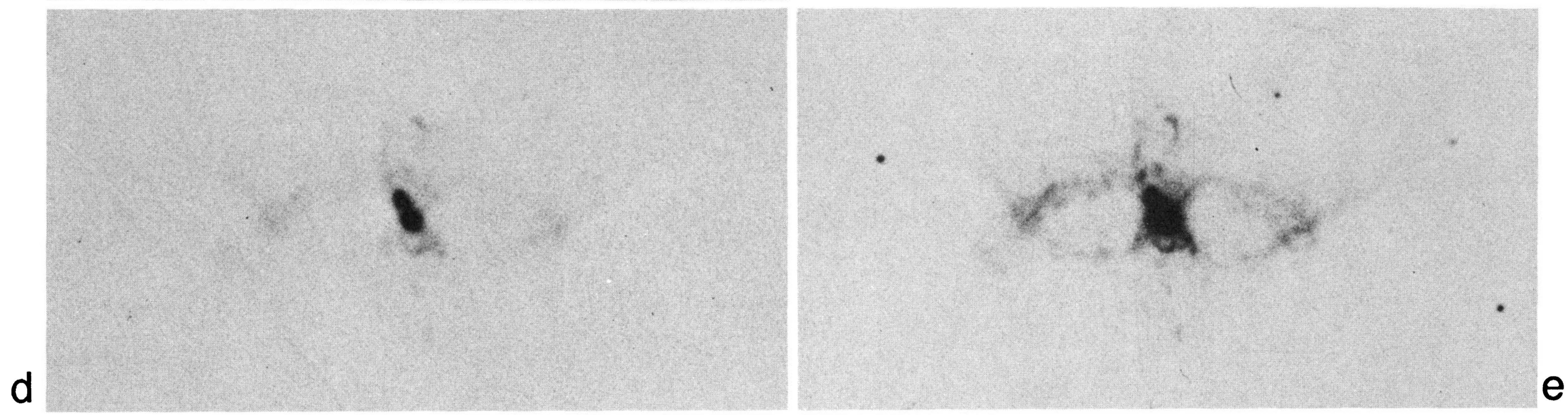


FIG. 2.—Direct photographs of the nebulosity at R Aqr, obtained from the Lick Observatory 120 inch (3 m) reflector. The three exposures on the left were obtained in the near-UV (3500–3900 Å) region, the two on the right in the red (6000–6800 Å). Two exposures, (*a*) and (*b*), were obtained in 1960 September 25 and September 17 respectively. Exposure (*c*) was obtained on 1970 September 8, and exposures (*d*) and (*e*) on 1980 October 18. The area shown is about 130″ × 230″; north is at the top and east to the right.



SOPKA *et al.* (*see* page L35)

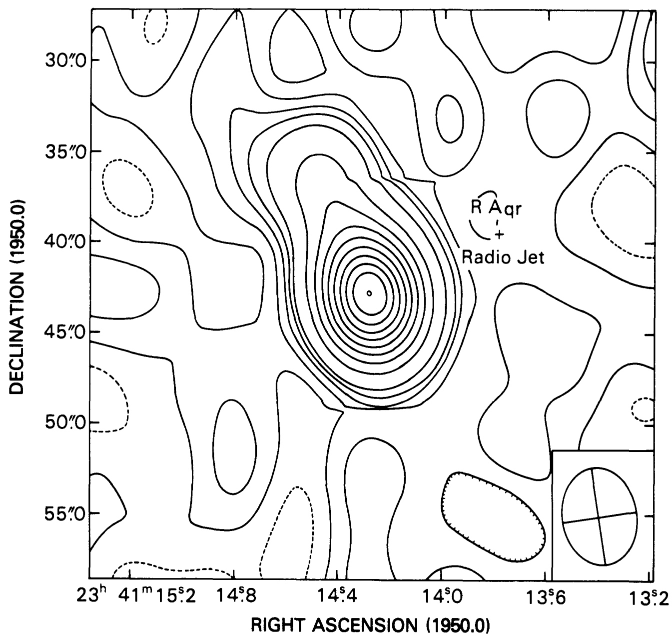


FIG. 1.—The 6 cm VLA map showing structure extending from the central source at R Aqr at p.a. ~ 24°. The contours are 100%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10%, 8%, 6%, 4%, 2%, 0%, and −2% of the peak intensity of 8.79 mJy per beam area. The beam pattern shown in the lower right has dimensions 5″.7 × 4″.5 and p.a. 8°.

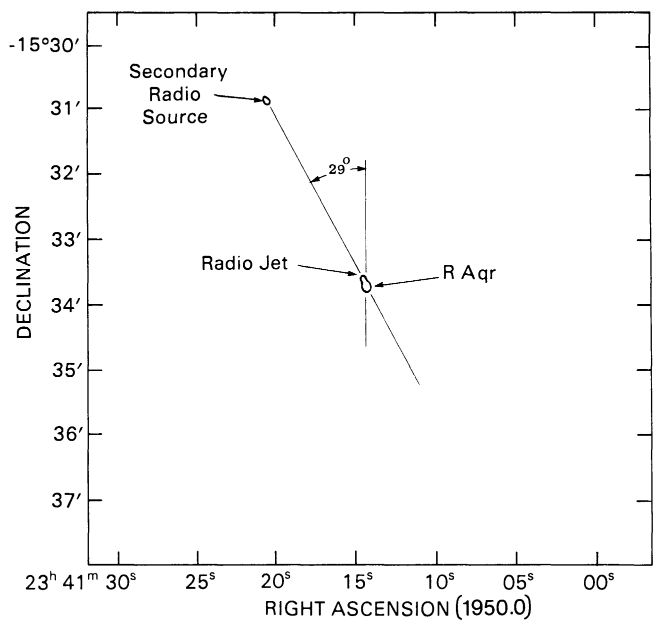


FIG. 3.—Wide-field 6 cm map of R Aqr showing another radio source. It lies at a p.a. of 29° with respect to the central source, nearly in the same direction defined by the axis of the jetlike feature.

TABLE 1

FLUXES OF RADIO FEATURES

FEATURE	$S_{6\,cm}$ (mJy)	$S_{2\,cm}$ (mJy)	$S_{1.3\,cm}$ (mJy)	RADIO PEAK POSITION R.A. (1950.0)	Decl. (1950.0)
R Aqr	9.3 ± 0.5^a	16.4 ± 0.8^a	22 ± 2.5^a	$23^h41^m14\overset{s}{.}269 \pm 0\overset{s}{.}005$	$-15°33'42\overset{''}{.}890 \pm 0\overset{''}{.}070$
Jet	2.3 ± 0.5^a	$\lesssim 2.4^b$	$\lesssim 7.5^b$		
Secondary source	2.6 ± 0.5^a	$\lesssim 2.4^b$	$\lesssim 7.5^b$	23 41 20.495 ± 0.030	−15 30 52.880 ± 0.500

[a]Background noise level of 1 σ rms (see text).
[b]Limits represent 3 σ.

Of additional interest is an unresolved source that appears in the wide-field 6 cm map (Fig. 3) approximately 3′ away at a position angle of ~ 29° with respect to R Aqr, placing it almost directly along the axis defined by the radio jet. Although the statistics of radio source counts lead to the expectation of an extragalactic background source at the 3 mJy level in a 10′ × 10′ field, the relationship of this secondary source to R Aqr (which itself shows extended optical nebulosity to ~ 1′) warrants further investigation. We find no evidence of this additional source on either the red or blue plates of the Palomar Sky Survey.

Table 1 is a compilation of the fluxes for the radio features described above at the three observing frequencies. The tabulated values were derived from a summation of the fluxes removed in the beam-cleaning process at the positions of the various features. The primary calibrator was 3C 48 whose flux was taken to be 5.36, 1.71, and 1.09 mJy at 6, 2, and 1.3 cm respectively.

Errors in the fluxes are primarily dictated by the characteristic system temperature at each frequency and were evaluated by inspection of the background field on both the dirty and clean maps. We arrived at the stated values by taking the extremes of the background noise away from the source and thus (conservatively) defining the 4 σ range of the random variations. The errors we present are rms values and the upper limits are 3 times the rms value.

A series of negatives taken with the Lick Observatory 120 inch (3 m) telescope is reproduced in Figure 2. The near-ultraviolet plates were exposed on Kodak 103a-O emulsion behind a Schott UG-1 filter. On account of the glass in the correcting lens system, the resulting bandpass is about 3500–3900 Å. The red exposures, on 103a-E or 103a-F emulsion behind a 2 mm RG-1 filter, have a bandpass of about 6100–6800 Å. They were taken near minimum light to resolve the inner nebulosity from the star.

On the 1960 plates, the brightest features of the inner nebulosity are the three knots or condensations (A at 8″ in p.a. 21°, B at 13″ in 22°, C at 24″ in 349°) and a peculiar, horseshoe-shaped loop open toward the star and extending about 8″ south. The most recent plates were taken on 1980 October 18. Mrs. Janet Mattei has kindly informed us that AAVSO observations show that minimum light occurred on 1980 October 21; the visual magnitude was 11.2 ± 0.3 on both dates.

It was immediately apparent at the prime focus of the 120 inch telescope, when centering R Aqr in preparation for the recent exposures, that there was a bright jet or appendage projecting slightly east of north. Both the red and the ultraviolet plates show the (overexposed) image of this protuberance to extend about 10″ from the star toward p.a. 22° (Figs. 2*d* and 2*e*). It is an order of magnitude higher in surface brightness, in both passbands, than any other part of the inner or outer nebulosity and seems to have two imperfectly resolved brightness peaks along its length, at about 6″ and 8″ from the star. There is a gap between the inner end of the jet and the star. Knot A, which had been measured at about 9″ in p.a. 25° on the ultraviolet plate of 1970, is now obliterated by the brilliant image of the jet.

Wallerstein and Greenstein (1980) reported detecting a "spike" of emission nebulosity extending north of R Aqr at the time of the deep minimum of 1977 September. They reproduced two direct exposures taken at that time in red light which in appearance are very similar to the 120 inch telescope red plates of 3 years later, and which leave no doubt that they were the first to discover the feature. Accurate measurements would be required to determine whether the radial extension of the spike was then the same. In any case, it is clear that the spike must have appeared between 1970 and 1977.

Two nights after the 1980 photographs were obtained, a series of 34 Å mm^{-1} spectrograms covering 5800–6800 Å was taken of the spike at the coudé focus of the 120 inch telescope, with the cooled Varo image intensifier. The 12″ long slit was successively oriented along a radius from the star in position angles 19°, 25°, and 31°. Sharp, intense emission lines of Hα, He I, [O I], [N II], [S II], and [S III] were strongest at positions along the slit corresponding to the spike and knot B. There is a clear radial velocity difference between the spike and the knot. Therefore, it is unlikely that the spike represents simply enhanced emission from knot A, although we cannot rule out this possibility. The spike velocity appears to depend either upon wavelength or upon the ion measured: [O I] gives −64; [N II], −71; Hα, −71; and [S II], −78 km s^{-1}; or −71 km s^{-1} (heliocentric) in the mean. Knot B shows a mean velocity of -24 ± 3 km s^{-1}, while the same lines in the star are near -44 ± 2 km s^{-1} on a plate obtained the same night. There is no detectable difference in velocity (greater than 2–3 km s^{-1}) between the two ends of the spike. Unfortunately, no spectrograms were obtained of the loop to the south of the star.

The direct plates show that knot B became fainter from 1960 to 1980 and is moving away from the star. Furthermore, the southern loop is slowly increasing in size and decreasing in UV brightness. Measurements show B moving outward at $0''.082 \pm 0''.014$ (s.d.) yr^{-1}, or 77 ± 13 km s^{-1} if a distance of 200 pc is taken. Similarly, the outer edge of the loop is moving away from the star at $0''.049 \pm 0''.012$ yr^{-1}, or 46 ± 12 km s^{-1}. At these tangential velocities, these two features would have left the vicinity of R Aqr in the years 1801 ± 21 and 1792 ± 32 respectively. Knot C is actually a curved filament, whose brightness structure appears to have changed slowly between 1960 and 1980, so the measurements of its position are suspect. Taken literally, they indicate motion of C away from R Aqr at $0''.27 \pm 0''.02$ yr^{-1}, or 254 ± 15 km s^{-1}, which leads to a departure date of 1872 ± 5. All of these results will be improved when the old photographs of the nebulosity can be combined with this new material. No attempt has been made to measure movement of the outer nebulosity, except to confirm that it is indeed in slow expansion as found by Hubble (1940, 1943) and Baade (1943, 1944).

III. DISCUSSION AND CONCLUSIONS

R Aqr is known to undergo erratic episodes in which the hot ionized source dominates the integrated visual light. In the 1928–1935 outburst, the optical spectrum was characterized by a blue continuum and hydrogen P Cygni profile emission lines dominating the normally strong absorption spectrum of the cool Mira variable (Mattei and Allen 1979). The light period of 387 days was still apparent during this outburst, although the amplitude of the variations decreased. Observations by Michalitsianos, Kafatos, and Hobbs (1980) with the *International Ultraviolet Explorer* (*IUE*) suggest that an inner ionized region, 2×10^{14} cm in extent, undergoes UV-photoexcitation by a hot subdwarf with an estimated $T_{\rm eff} = 5 \times 10^4$ K to 10^5 K. Episodic mass transfer which forms an accretion disk around the hot secondary may account for the strong outburst emission phases.

We find that the Mira variable fails to fill its Roche lobe by a factor of 5–7. The possibility remains, however, that the orbit is highly elliptical (cf. Merrill 1950; Willson, Garnavich, and Mattei 1981), and the Mira variable fills its Roche lobe only at periastron.

Radial velocity measurements of R Aqr in the next 10–20 years would be important to determine if the eclipse of 1978 (Willson *et al.*) took place near periastron. In this case, the appearance of the jetlike feature near the time of eclipse could be explained as resulting from supercritical accretion (cf. Bath 1977) onto the hot secondary.

If we take 7″ as the extent of the radio jet and assume this is the distance traveled in the last 10 years, then the velocity of the radio jet is ~ 700 km s^{-1}. If we assume that the absence of the optical jet feature on the Lick plate of 1970 and its appearance in the 1980 exposure are consequences of mass motion, then the tangential velocity must be ≥ 300 km s^{-1}. We emphasize, however, that there is neither a suggestion for velocities of this magnitude from spectroscopic evidence nor are these velocities normally found in symbiotics. As such, the appearance of the radio-optical jet may have been caused by the sudden ionization of gas that is moving outward at more moderate velocities.

Because of its relatively close proximity of ~ 200 pc, it may be possible to resolve spatially an accretion disk near R Aqr either with the Space Telescope or from the ground with optical interferometry techniques. If all of the UV continuum seen by Michalitsianos *et al.* comes from the disk, we estimate on the basis of theoretical work by Mayo, Wickramasinghe, and Whelan (1980) that $m_B \sim 12$ for the disk. At minimum light, the Mira variable should have $m_B \sim 15$. Using numbers quoted previously, we estimate the extent of the accretion disk to be $\sim 0''.1$. The direct observation of the accretion disk in SS 433 and all disks in active galactic nuclei will be impossible for some time to come. The R Aqr jet, therefore, is extremely important because it may provide the only opportunity to check directly the physics of accretion disks and subsequent jet formation. Work is proceeding with both the *IUE* and the VLA to observe this jetlike feature.

We acknowledge the assistance of C. Jarrett, P. Angerhofer, P. Palmer, and the staff of NRAO-Charlottesville for their generous help with the data reduction. B. Zuckerman originally suggested that VLA observations of R Aqr might be of interest and offered helpful comments during the course of the project and development of the manuscript. VLA is operated by the National Radio Astronomy Observatory which is operated by the Associated Universities, Inc., under contract with the National Science Foundation. R. J. S. acknowledges partial support for this work under NSF grant AST 80-23355 to the University of Maryland.

REFERENCES

Baade, W. 1943, *Ann. Rept. Dir. Mt. Wilson Obs.*, 1942–1943, p. 17.
______. 1944, *Ann. Rept. Dir. Mt. Wilson Obs.*, 1943–1944, p. 12.
Bath, G. T. 1977, *M.N.R.A.S.*, **178**, 203.
Hubble, E. P. 1940, *Ann. Rept. Dir. Mt. Wilson Obs.*, 1939–1940, p. 19.
______. 1943, *Ann. Rept. Dir. Mt. Wilson Obs.*, 1942–1943, p. 17.
Mattei, J. A., and Allen, J. 1979, *J.R.A.S. Canada*, **73**, 173.
Mayo, S. K., Wickramasinghe, D. T., Whelan, J. A. J. 1980, *M.N.R.A.S.*, **193**, 793.
Merrill, P. W. 1950, *Ap. J.*, **112**, 514.
Michalitsianos, A. G., Kafatos, M., and Hobbs, R. W. 1980, *Ap. J.*, **237**, 506.
Thompson, A. R., Clark, B. G., Wade, C. M. and Napier, P. J. 1980, *Ap. J. Suppl.*, **44**, 151.
Wallerstein, G., and Greenstein, J. L. 1980, *Pub. A.S.P.*, **92**, 275.
Willson, L. A., Garnavich, P., and Mattei, J. A. 1981, *Inf. Bull. Var. Stars*, p. 1961.

Note added in proof.—(1) Dr. J. L. Greenstein has kindly informed us that it is his impression that the new, high surface brightness knot "was definitely fainter in 1977 September than on the Lick photographs in 1980." Therefore, a substantial part of its increase in brightness must have occurred in the intervening 3 years. (2) We understand that the radio jet in R Aquarii was also observed by D. N. Spergel and G. R. Knapp, Princeton University, during the same epoch.

G. HERBIG: Lick Observatory, University of California, Santa Cruz, CA 95064

M. KAFATOS: Department of Physics, George Mason University, Fairfax, VA 22030

A. G. MICHALITSIANOS: Code 685, Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771

R. J. SOPKA: Natural Sciences Division, Catonsville Community College, 800 South Rolling Road, Catonsville, MD 21228 (for preprints)