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FY AQUILAE AND THE GAMMA-RAY BURST EVENT OF 1979 MARCH 31¹

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ABSTRACT

We present deep CCD images, spectrophotometry, and astrometry of the variable star FY Aquilae, which is located within the error box of the 1979 March 31 gamma-ray burst event. Deep red CCD images reveal that FY Aql is surrounded by a faint, extended nebulosity centered on the variable star. Spectrophotometry of FY Aql and its nebulosity suggests that it is an M4e III Mira variable star embedded in an extended reflection nebula. We argue that there is at present no compelling observational evidence to suggest that this system is the optical counterpart of the 1979 March 31 gamma-ray burst.

Subject headings: gamma-rays: bursts — nebulae: reflection — stars: individual (FY Aql)

I. INTRODUCTION

With the advent of precise localizations for a few gamma-ray bursts from multisatellite triangulation, deep searches for optical counterparts became feasible. In spite of great efforts no unambiguous identification has yet been made (e.g., Hurley 1986 and references therein). Attempts to associate an object with a gamma-ray burst source rely on the presence of objects with peculiar properties, such as unusual temporal behavior, high proper motion, large degrees of polarization, extreme colors, unusual spectral features or peculiar morphological appearance. While there is no real reason to suspect that a quiescent counterpart must of necessity be unusual, given the large number of objects which may be present in an error box, this provides a sensible starting point. As long as we lack knowledge of what gamma-ray burst sources looks like in quiescence, it will remain difficult to perform meaningful observations of their error boxes. A detailed account of the dilemma is given by Hurley (1986).

Laros *et al.* (1985) determined the locations of five gamma-ray bursts that occurred in 1979 March with error boxes small enough to encourage further observations at other wavelengths. The authors reported on selective catalog searches on ~35,000 objects in these boxes, including pulsars, flare stars, variable stars, X-ray sources, and radio sources. One association was found inside the box of GB 790331, namely, the star FY Aql, which had been previously cataloged as a Mira variable with a period of 208 days (Ahnert-Rohlfs and Götz 1954). Based on the archival data of the Harvard plate collection and from the fact that they could not identify FY Aql in the crowded field, the authors concluded that FY Aql is most likely a dwarf nova. They obtained neither spectral nor photometric data on FY Aql at that time.

During a CCD imaging search for possible optical counterparts in the three northern hemisphere error boxes of the Laros *et al.* (1985) list (the full results of which will be published elsewhere), our images of the GB 790331 error box revealed a faint nebulosity centered on FY Aql, whose identification we obtained from the finding charts in the discovery paper of Wolf and Wolf (1905). According to the general criteria discussed above, this discovery suggested the exciting possibility that a possible gamma-ray burst counterpart might have been found.

It is well known that circumstellar shells are common around Mira variables (Hoffmeister, Richter, and Wenzel 1985), but it also appeared possible that FY Aql may be a symbiotic system, like R Aquarii or AG Pegasi. These latter two objects are presently thought to represent binary systems consisting of either a late-type M giant, or a long-period Mira variable primary, and a hot secondary star, embedded in a compact H II region (Michalitsianos, Kafatos, and Hollis 1986). Ejection of matter in the form of “jets” has been observed in these systems. Although it is widely believed that the majority of gamma-ray bursts originate on or near the surface of neutron stars (e.g., Lamb 1984; Woosley 1984), given our present state of understanding, an association with other objects known to produce energetic phenomena is not entirely out of the question.

In light of the renewed interest in this object expressed in the most recent literature (e.g., Schaefer *et al.* 1987), we present imaging and photometry of FY Aql and its field and subsequent spectrophotometric observations aimed at firmly establishing the nature of FY Aql and its surrounding nebulosity. In § II below we present details of the imaging, spectrophotometric and astrometric observations. In § III we present the data and make an estimate of the distance to FY Aql. In § IV we discuss our results, give an estimate of the mass of the nebulosity, and make a few concluding comments on the nature of this object and its relationship to gamma-ray burst sources.

II. OBSERVATIONS

a) Direct Images

Direct images of the GB 790331 gamma-ray burst error box which includes FY Aql were made with the 1 m Anna Nickel telescope of Lick Observatory using a Texas Instruments 500 × 500 three-phase CCD detector with the f/17 Cassegrain CCD spectrograph and 110 mm Hasselblad focal reducing lens. This direct imaging mode of the spectrograph provides an image scale of 1".1 pixel⁻¹ at an effective focal ratio of f/2.5. On 1986 May 12 UT we obtained one 300 s exposure through a Gunn *r*-filter (Thuan and Gunn 1976) and two exposures of 60 s and 300 s each through a *V* band filter (2 mm GG 495 + 2 mm BG 18). *UBVRI* standard star fields in M92 and NGC 4147 (Christian *et al.* 1985) were observed to provide a flux calibration of our images. Additional CCD images with

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the same instrument were generously obtained for us by Jon Holtzman on 1986 June 17 UT. Two exposures of 40 s and 160 s duration were taken through the same Gunn *r*-filter as above, and a 120 s exposure was taken through a 100 Å wide interference filter in the region of the H α + [N II] $\lambda\lambda$ 6548, 6583 emission lines. Conditions for both nights were clear and photometric, with seeing of $\sim 2''$.

Basic reduction of the CCD images was straightforward. Each CCD frame was divided by an appropriate flat-field frame taken of the twilight sky. Difficulties with the dome lamps not providing uniform illumination precluded the use of dome flat-field exposures. Cosmic-ray events and known bad pixels were removed interactively. Fringing was not significant in the regions of interest on these images. The two 1986 May 12 *V* band filter images were co-added to produce an effective 360 s exposure, and the two 1986 June 17 Gunn *r* band images were co-added in a similar fashion. In these and the spectral observations described below, we used the interactive image reduction and analysis program VISTA developed at Lick Observatory.

b) Spectrophotometry

We have obtained four spectra scans of FY Aql, two of the star and two of the surrounding nebulosity, with the 3 m Shane telescope of Lick Observatory. All spectra were taken with the transmission CCD spectrograph using a 240 line mm $^{-1}$ grism which gives a dispersion of ~ 5 Å pixel $^{-1}$ in the spectral range of 4000–7800 Å. The detector was a Texas Instruments 800 $\times$ 800 three-phase CCD (Lauer *et al.* 1984). A 2" wide slit was used to provide an effective instrumental resolution of 10 Å. On 1986 July 3 UT we obtained the two spectra of FY Aql with exposures of 120 s and 180 s. These spectra were co-added to produce a single 300 s exposure. On 1986 July 31 UT, we obtained spectra of the nebulosity around FY Aql using a 2' long slit positioned 3" northwest of the star at a position angle of 40°. Seeing on this night was excellent, less than 1". Two exposures of 600 s and 1200 s duration were co-added to produce a single 1800 s exposure.

The data were reduced as follows: each image was divided by the appropriate flat-field (quartz lamp) exposure. The relevant spectral rows in each image were added together and sky-subtracted to produce a raw spectrum. Each spectrum was then placed on a linear wavelength scale using dispersion curves fit to spectra of comparison lamps taken at the beginning of the night to obtain the overall dispersion, and using night sky lines recorded on each spectral image to derive the zero points. The counts were transformed to units of energy per unit area per time per unit wavelength using standard stars taken at the beginning and ending of the night. The atmospheric *A* and *B* bands were removed by dividing the spectra by these same standard stars. While the data were taken during nights of good seeing and photometric conditions, the expected spectrophotometric accuracy of these techniques is $\sim 10\%$.

c) Astrometry

The only previously reported coordinates for FY Aql are given in Wolf and Wolf's 1905 discovery paper. Because there seems to be some confusion about the location of FY Aql due to its being situated in a relatively crowded field (Laros *et al.* 1985), we have measured an accurate astrometric position from plates taken of the field with the Lick 20 inch Astrograph as part of the second-epoch phase of the Lick Northern Proper Motion Program (Vasilevskis 1973). Because of FY Aql's close

proximity to the northeast of a star of similar brightness ($V = 15.02 \pm 0.05$ from this study), measurement with the Gaertner automatic measuring machine was not possible, but the field could be easily measured manually using the Gaertner survey machine at Lick (Vasilevskis and Popov 1971; Klemola, Robinson, and Vasilevskis 1974). The resulting position for equinox 1950.0 of FY Aql, measured with respect to 18 stars from the AGK3 Catalog (Dieckvoss *et al.* 1975) to an accuracy of $\sim 0''.3$ – $0''.4$ in both coordinates, is given in Table 1. We were further assured of our correct identification of FY Aql by noting that the star was clearly red in color by visual comparison of the blue and yellow second-epoch Lick Astrograph plates, and the obvious variability evident between the first-epoch (1949.64) and second-epoch (1977.47) blue plates.

III. DATA

In Figure 1 (Pl. 4) we show the *V*-band (Fig. 1a), Gunn *r* band (Fig. 1b), and H α (Fig. 1c) images of FY Aql and its surroundings. A faint nebulosity can be seen in the region surrounding FY Aql (the northeast component of an apparent double) in the Gunn *r* frame (Fig. 1b) but not in either the *V*-band or H α images. For the *V*-band image, we derive an upper limit on the surface brightness of the nebulosity of 23.4 mag arcsec $^{-2}$, our detection limit for this image. The lack of a detection of the nebulosity in the H α image strongly suggests that it is not emission-line gas but rather is a reflection nebula, which is confirmed by the spectrophotometry presented below. Photometric reductions of the images were made using the Stetson DAOPHOT program. Photometry of FY Aql and the nebulosity in the *V* and Gunn *r* band images are given in Table 2. For the night with spectrophotometry, we have estimated *V* and *r* magnitudes using our filter response curves. A summary of the observed properties of FY Aql and its nebulosity are given in Table 1.

The photometry in the Gunn *r* band shows that FY Aql was steadily increasing in brightness over the period covered by our observations. While subject to a somewhat greater uncertainty, the *V* magnitude derived from our spectrum indicates that FY Aql was about at maximum light based on previous observations (Ahnert-Rohlfs and Götz 1954).

TABLE 1
SUMMARY OF PROPERTIES

FY Aql	
α (1950.0)	19 ^h 25 ^m 30 ^s .98 $\pm$ 0 ^s .02
δ (1950.0)	+03°35'48".2 $\pm$ 0".3
l^{II}	40°434
b^{II}	−6°414
Spectral type	M4e III
Variable type	Mira
Period	208 days ^a
$E(B-V)$	0.5 $\pm$ 0.1
M_p	−1.7 $\pm$ 0.2 ^b
Distance	4 $\pm$ 1 kpc
Nebulosity	
Type	Reflection
Angular diameter	30" ^c
Physical diameter	0.64 $\pm$ 0.16 pc
Surface brightness in Gunn <i>r</i> band	21.3 $\pm$ 0.1 mag arcsec $^{-2}$

^a Ahnert-Rohlfs and Götz 1954.

^b From method of Celis 1980.

^c From outermost isophote 3 σ above detection limit.

PLATE 4

FIG. 1.—Direct CCD images of the region of the GB 790331 error box around FY Aql, in (a) the V -band, (b) the Gunn r -band, and (c) a $100 \text{ \AA}$ wide $H\alpha$ interference filter band. As first determined by Wolf and Wolf (1905) the FY Aql is the NE component of the apparent double. A faint nebulosity surrounding FY Aql can be seen in the Gunn r -band image (b) but not in either the V -band (a) or the $H\alpha$ (c) images. In all of these images, north is up and east is to the left. The image scale is $1''.1 \text{ pixel}^{-1}$. The scale bar indicates $20''$ on the sky.

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TABLE 2
PHOTOMETRY OF FY AQUILAE AND ITS NEBULOSITY

UT DATE (1986)	TELESCOPE (m)	MAGNITUDES ^a		
		<i>V</i>	<i>r</i>	(<i>V</i> − <i>r</i>)
FY Aql				
May 12.493	1	16.6 ± 0.1	14.9 ± 0.1	1.7 ± 0.1
June 17.428	1	...	13.5 ± 0.1	...
July 3.364	3 ^b	12.8 ± 0.1	11.5 ± 0.1	1.3 ± 0.2
Nebulosity ^c				
May 12.492	1	... ^d	21.3 ± 0.1	...
June 17.428	1	...	21.4 ± 0.1	...
July 31.424	3 ^b	...	21.0 ± 0.2	...

^a Magnitudes and colors uncorrected for interstellar extinction.

^b Magnitudes and colors derived from spectrophotometry.

^c Surface brightness in a nebular region free of foreground stars in units of magnitudes arcsec^{−2}.

^d Nebulosity undetected in the *V* band.

Figure 2 shows an isophotal contour map of the Gunn *r* image of FY Aql and the faint nebulosity. The isophotes of the nebulosity are clearly centered on FY Aql. Our identification of FY Aql is confirmed by the finding chart and description of Wolf and Wolf (1905). The nebulosity is round in appearance and has an apparent angular diameter of 30"—the "edge" taken to be the isophote enclosing pixels above the estimated

3 σ detection limit of 22.2 mag arcsec^{−2} in the *r* band filter. The field is very crowded, and most of the features in the nebulosity are apparently due to foreground and background stars. We therefore suggest that, to our ability to spatially resolve it, the nebulosity is essentially featureless. To within the uncertainties in our measurements, the surface brightness of the nebulosity has remained unchanged at $\sim 21.3 \pm 0.1$ mag arcsec^{−2} in the *r* band over the 2.5 month period of our observations.

Figure 3 shows a low-resolution spectrum of FY Aql covering the spectral range of 4000–7800 Å. The spectrum is dominated by a red continuum with deep TiO absorption bands. In the blue, the H γ λ 4340 and H δ λ 4102 Balmer lines of hydrogen are clearly in emission. Between them, the Ca I λ 4226 line is seen weakly in absorption. All of these features suggest that FY Aql is a Mira type variable, following the classification criteria of Keenan, Garrison, and Deutsch (1974). Using MK spectral standards, we place the spectral classification of FY Aql at the time our spectra were obtained as M4e III, using the M4 III star HR 832 as a template. This spectral type is fully consistent with the reported period of 208 days (Celis 1980). The absence of H α and H β Balmer emission lines given the presence of the H γ and H δ lines is not at all surprising. In the atmospheres of Mira type stars, the hydrogen Balmer lines are shock excited in the atmosphere, but H β and H α emission is suppressed by the presence of TiO (e.g., Wood 1979).

Figure 4a shows the spectrum of the nebulosity surrounding FY Aql. In the red end of the spectrum the appearance of a

FIG. 2.—Isophotal contour map of the field surrounding FY Aql in the Gunn *r* band image of 1986 May 12.493 UT. The exposure time is 300 s. The outermost isophote is at a level of 22.2 mag arcsec^{−2}, and the contours are spaced at intervals of 0.5 mag arcsec^{−2}.

FIG. 3.—Low-resolution spectrum of FY Aql taken on 1986 July 3 UT. The spectral type of FY Aql on this date was M4e III. Strong TiO absorption bands, suppressed H α and H β lines, strong (shock-excited) higher order Balmer lines in emission, and the Ca I λ 4227 line in absorption are all apparent.

band structure like that in Figure 3 is apparent. There is no evidence of any emission lines in this nebulosity. Figure 4b shows the ratio of the nebular flux to the stellar flux in 80 Å bands centered at intervals of 100 Å, obtained by dividing the nebular spectrum by the high signal-to-noise spectrum of FY Aql shown in Figure 3. Despite the greater noise at the blue end, there is a distinct systematic rise to the blue, indicating that the nebulosity has a bluer spectrum than FY Aql. This is the characteristic signature of a reflection nebula. The clear lack of any emission lines further strengthens this conclusion.

Given that our observations seem to have been taken around maximum light, we may use our spectral classification to make an estimate of the distance to FY Aql. Because of its low galactic latitude ($b \approx -6^\circ$), it is subject to a significant interstellar extinction. Bessel (1979) gives the $(V-R)$ color for an M4.5 III star. Using the transformation equations of Kent (1985) between the Gunn r band and Cousins R band, this gives us an intrinsic $(V-r)$ color of an M4 III star of ~ 1.03 . Assuming a Savage and Mathis (1974) extinction curve, this gives a relation between the color excess between the V and Gunn r bands, and the usual $(B-V)$ color excess. Using the observed $(V-r)$ color of 1.7 (Table 2), this gives an approximate $E(B-V)$ in the direction of FY Aql of $\sim 0.5 \pm 0.1$, hence a total extinction in the V band of $A_v = 1.6 \pm 0.1$ mag.

On 1986 July 3.364 UT, we observed a V -magnitude of 12.8 ± 0.1 mag (Table 2), implying an apparent V -magnitude of ~ 11.2 mag using the extinction correction derived above. Following the period-spectral type-luminosity relation for Mira variables derived by Celis (1980), we estimate an absolute V band magnitude of $M_v = -1.7 \pm 0.2$, using the observed spectral type of M4e III and a period of 208 days. Thus, we

derive a distance of $\sim 4 \pm 1$ kpc to FY Aql. This uncertainty is typical of distances determined in this way (Celis 1981).

This distance estimate allows us to make an estimate of the physical size of the nebulosity surrounding FY Aql. Given an apparent angular diameter of the nebulosity of $30''$, at a distance of 4 kpc this implies a physical diameter of $\sim 0.64 \pm 0.16$ parsecs, hence a radius of ~ 0.3 pc or $\sim 60,000$ AU. We have searched the IRAS Point Source Catalogue within a radius of $5'$ of FY Aql for possible IR counterparts. No candidates were identified.

IV. DISCUSSION

It is well known that red giant stars in general, and Mira variables in particular, possess circumstellar dust shells and are subject to substantial mass loss (see Reimers 1977a for a detailed discussion). The existence of these shells may be inferred from the detection of maser emission in OH, H₂O, and SiO lines at radio wavelengths (e.g., Engels 1979), and typical dimensions have been estimated to be of order 10^{16} cm for Mira variables (e.g., Herman and Habing 1985). In contrast, reflection nebulae around late-type giants seem to be rather rare phenomena (Dachs and Isserstedt 1973; Reimers 1977b) and their diameters are much larger (e.g., 0.2 pc for IC 2220; Dachs and Isserstedt 1973). In this regard, the FY Aql system may constitute a potentially interesting opportunity to study the interaction between slow mass loss from a late-type variable star and the interstellar medium relatively high above the galactic plane (~ 400 pc for a distance of 4 kpc and $b \approx -6^\circ$).

If we assume that mass loss from FY Aql accounts for the reflection nebula—its location at the precise center of the nebula argues in favor of this interpretation, whereas statistical

FIG. 4a

FIG. 4b

FIG. 4.—(a) A low-resolution spectrum of the extended nebula around FY Aql in the spectral range 4000–7800 Å. No emission lines are present, and the red end of the spectrum shows band structure like that seen in the spectrum of FY Aql (Fig. 3). (b) The ratio of the nebular flux to the stellar flux in 80 Å bands centered at intervals of 100 Å. The distinct systematic rise to the blue is characteristic of a reflection nebulae.

arguments appear to favor the opposing point of view (Reimers 1977b)—we can get an estimate of the mass of the nebulosity in the following way. From the observed linear scale of the nebula ($R \approx 10^{18}$ cm), together with typical mass-loss rates from Mira variables of order $3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ (Gehrtz and Woolf 1971) and wind velocities $v \approx 5 \text{ km s}^{-1}$ appropriate for periods of ~ 200 days (Wood 1979) we obtain for the mass shed by FY Aql

$$M_{\text{shed}} \sim \frac{R\dot{M}}{v} \sim 3 \times 10^{-2} M_{\odot}.$$

As a result of this continuous mass loss (over a period of $\tau = R/v \approx 10^5$ yr) a shell of compressed interstellar matter is formed by the snowplow effect of the stellar wind (e.g., Kafatos, Michalitsanos, and Vardya 1977). With a reasonable estimate of the density of the interstellar gas ($n_0 \approx 0.04 \text{ cm}^{-3}$ at the appropriate galactic scale height), the amount of gas swept up is

$$M_{\text{swept}} \approx 6 \times 10^{-3} n_0^{1/4} (\dot{M}_{-7} v)^{3/4} \tau_5^{3/2} M_{\odot} \approx 2 \times 10^{-2} M_{\odot}.$$

The total mass of the reflection nebula around FY Aql estimated in this way would be of the order of $0.05 M_{\odot}$.

We do not confirm the earlier suggestion that FY Aql may be a cataclysmic variable (Laros *et al.* 1985). This conclusion of Laros *et al.* was based solely on their inspection of archival Harvard plates which showed the star near the faint phase a larger fraction of the time ($\leq 90\%$) than might be consistent with its identification as a regularly varying Mira star, and on their observation that FY Aql appeared relatively blue on the Palomar Observatory Sky Survey (POSS) plates. The authors also noted that they did not succeed in finding the variable star in the crowded field. Furthermore, their reference to Mayall's (1951) identification of FY Aql as a Mira is puzzling as Mayall does not make any mention of this object whatsoever.

We have unambiguously identified FY Aql on direct CCD images (§ III), determined an accurate astrometric position (§ IIc), and obtained spectrophotometric data (§ IIb). This body of data leaves no doubt that FY Aql is in fact an early M-type Mira variable. The "apparent" blueness of FY Aql mentioned by Laros *et al.* (1985), and also more recently by Schaefer *et al.* (1987), is the result, we believe, of a misidentification of the variable star. FY Aql is the northeast component of an apparent duplex (Wolf and Wolf 1905). Our photometry of the southwest star indicates that it is relatively much bluer than FY Aql [$(V-r) = 0.35$ compared to 1.5 for FY Aql]. At the scale of the POSS plates, this duplex is not at all evident, the image apparently dominated by the southwest star. On the Lick proper motion survey first and second epoch 20 inch Astrograph plates, the duplex is clearly resolved.

Even though reflection nebulae around late-type stars are rare, we do not think that this alone is compelling observational evidence to suggest the FY Aql itself is the source of the 1979 March 31 gamma-ray burst. On the other hand, the relatively dense circumstellar environment offers a potential site for such activity that cannot be ruled out entirely. In particular, FY Aql through the agency of its wind-fed circumstellar

nebulosity, could potentially act as a mass donor to an unseen compact companion, possibly a neutron star. If the mass loss via a wind as described above is in a steady state, then the mass-loss is related to the density and velocity of the wind by

$$\dot{M} = 4\pi r^2 \rho v.$$

The density of the medium surrounding a neutron star orbiting a distance R from FY Aql would then be given by

$$\rho \approx 10^{-14} R_{\text{AU}}^{-2} \text{ g cm}^{-3},$$

for a typical Mira mass loss rate of $\sim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ and wind velocity of $\sim 5 \text{ km s}^{-1}$.

Even if the neutron star is on an eccentric orbit and thus only spends a small fraction of its orbital period within the higher density regions of the Mira's wind zone, it may still be possible for it to accrete sufficient matter to produce an occasional burst either by accretion instability ($\sim 10^{18}$ g) or thermonuclear explosion ($\sim 10^{20}$ g). The density of this region also suggests that if the burst were to occur within the confines of the nebulosity, the interaction of the gamma-rays with the ambient dense medium may produce secondary optical effects whose detailed treatment is beyond the scope of our present discussion. Given the present state of the observational data, this scenario remains a speculative, although interesting, possibility.

Note added in manuscript.—We have recently been informed by Bradley Schaefer (NASA/Goddard Space Flight Center) that our conclusion that FY Aql is a Mira type variable has led him to examine the Harvard archival plate material for the FY Aql field. His preliminary results independently confirm our classification of FY Aql. In particular the period and phase derived from his photographic light curve indicate that our spectra were indeed taken very nearly at maximum light as we had supposed. Details of his analysis are being prepared for publication (Schaefer 1987).

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