1983ApJ...266L..27M

THE ASTROPHYSICAL JOURNAL, 266:L27–L31, 1983 March 1

PERIODIC VARIABILITY OF THE X-RAY NOVA A0620−00 IN QUIESCENCE

J. E. MCCLINTOCK, L. D. PETRO,[1] R. A. REMILLARD, AND G. R. RICKER
Department of Physics and Center for Space Research, Massachusetts Institute of Technology
Received 1982 August 19; accepted 1982 October 29

ABSTRACT

We have discovered periodic, photometric variations with a full amplitude of ~ 0.2 mag in the X-ray nova A0620−00 in its quiescent state. The most probable period is 7.8 hr, although there are several additional candidate periods. The broad-band (4000–6400 Å) observations were made on six consecutive nights in 1981 October–November with the 1.3 m McGraw-Hill telescope and the MIT CCD system (MASCOT). It is possible that the light curve is due to ellipsoidal variations of the K dwarf caused by the tidal forces of the neutron star. If so, the relatively large amplitude implies that the K dwarf fills a substantial fraction of its Roche lobe and that the orbital inclination of the system is large. It is also possible that the light curve is due to an eclipse in which the two light sources are the K dwarf and the accretion disk.

Subject headings: stars: novae — stars: variables — X-rays: binaries — X-rays: sources

I. INTRODUCTION

The X-ray nova A0620−00 was discovered on 1975 August 3 by *Ariel 5* (Elvis *et al.* 1975). It rose to its maximum intensity in 10 days and became the brightest X-ray object in the sky. At that time, it was identified optically with a blue star of 12th magnitude (Boley *et al.* 1976). During the following few months, its X-ray intensity decreased with a $1/e$ decay time of about 1 month, and its optical intensity decreased at about half that rate (for details see Whelan *et al.* 1977). In quiescence, the optical intensity of A0620−00 is $B \approx 19.7$, $V \approx 18.3$ (Murdin *et al.* 1980). Spectra obtained in 1976 and 1978 show absorption lines characteristic of a K5 V star and emission lines characteristic of an accretion disk (Oke 1977; Whelan *et al.* 1977; Murdin *et al.* 1980). The Eddington-limited X-ray luminosity at maximum establishes that the compact object is a neutron star. The distance to A0620−00 is ~ 900 pc, and the reddening is $E(B - V) = 0.39$ (Oke 1977, and references therein). An earlier outburst of the system was discovered on Harvard patrol plates taken in 1917 (Eachus, Wright, and Liller 1976). An 8.2 hr X-ray period has been suggested for Cen X-4 (Kaluzienski, Holt, and Swank 1980), an X-ray nova which is very similar to A0620−00. In this *Letter*, we present evidence for a comparable period in A0620−00.

II. OBSERVATIONS

We made photometric observations of A0620−00 on six consecutive nights beginning on 1981 October 29 UT using the f/7.5 Cassegrain focus of the McGraw-Hill 1.3 m telescope and a CCD camera, the MASCOT (Ricker *et al.* 1981, and references therein). Typically, a dozen 15 minute exposures were made during the latter half of each night. Sky conditions were photometric on four nights (October 29 and November 1–3) and nearly photometric on the other two nights. Throughout the observations, the seeing was stable (~ 2.″5 FWHM) and the sky was moonless. A broad-band filter and the response of the CCD detector gave a bandpass of 4000–6400 Å (FWHM). The detector is a Texas Instruments, 490 × 328, virtual phase CCD with an average quantum efficiency of 45% in this band. The array elements are 25 μm × 25 μm which corresponds to 1.2 arcsec^2 pixels for the optical configuration which we used.

We selected four reference stars (designated Y, T, S, and H) which are within 2.′1 of A0620−00. A flat-field frame was used to calibrate the relative response of the individual pixels, and a dark (unexposed) frame was used to correct for the detector bias level and any residual dark current (Ricker *et al.* 1981). The intensities of A0620−00 and the reference stars were obtained by summing the signal in a 9 pixel by 9 pixel box (11″ × 11″) centered on the star in question and by subtracting the background signal measured in two neighboring, 9 pixel by 4 pixel boxes. The derived intensities are shown in Figure 1. The intensities are expressed in instrumental units, ADU/900 s (1 ADU, or analog-to-digital converter unit, corresponds to 31 detected photons). Variations in the intensity of A0620−00 as large as 0.3 mag occurred during the six observing nights from a minimum of about 1500 to a maximum of 2000 ADU/900 s (Fig. 1). On several occasions, the intensity increased or decreased between the extreme values on a time scale of

---

[1] Present address: Atmospheric and Environmental Research, Inc., 840 Memorial Drive, Cambridge, Massachusetts 02139.

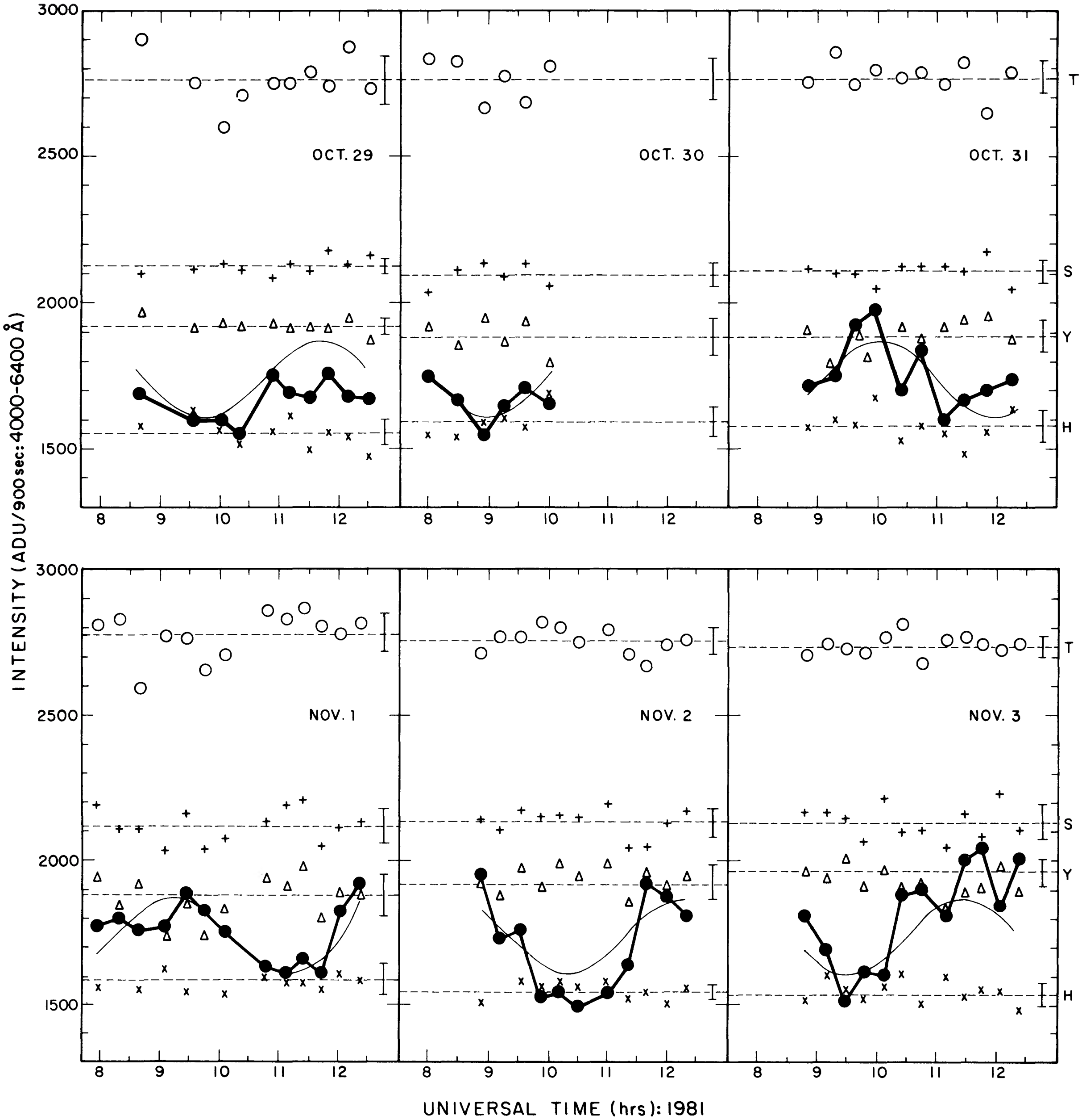

FIG. 1.—The intensities of A0620−00 and four reference stars (T, S, Y, and H) measured on six consecutive nights in instrumental units (see text). An approximate correction has been made for absorption by the Earth's atmosphere (0.2 mag per unit air mass). The air mass was between 1.2 and 1.6 which corresponds to a relative correction of < 7%. The average intensities of the reference stars for each night are indicated by horizontal lines. The standard deviation about the nightly mean, which is approximately 2% to 3%, is also shown.

~ 1 hr. In comparison, the standard deviation in the intensities of the reference stars was ~ 0.02–0.03 mag, and systematic variations in their intensities are not apparent.

We searched for periodicities by making a least squares fit to the six nights of data using a sine-cosine series in ω, 2ω, 3ω, etc., for a wide range of trial periods. We computed the reduced chi-square value (χ_ν^2) using the average of the standard deviations derived for the reference stars, which is 2.6%. The 62 data points were weighted equally. The results for a period search which included the fundamental term only are shown in Figure 2*a*. The minimum value of χ_ν^2 occurs for a period of 3.9 hr. The primary minimum is flanked

1983ApJ...266L..27M

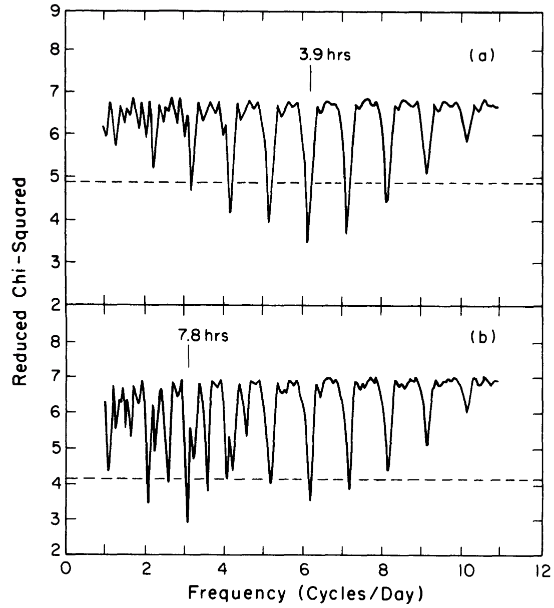

FIG. 2.—(*a*) The results of a period search in which only the fundamental term of a sine-cosine series was fitted to the six nights of A0620−00 data for a wide range of trial periods. The minimum value of χ_ν^2 is 3.5 and occurs at a period of 3.9 hr. The *F*-test may be used to reject values of reduced χ^2 which lie above the dashed line at the 90% confidence level. There are five additional candidates for the correct period for which the value of χ_ν^2 falls below the dashed line. The multiplicity is due to the data sampling (see text). (*b*) Same as (*a*) except the first harmonic terms are included. Compared with the results shown in Fig. 2*a*, the minimum value of χ_ν^2 is less (2.9 vs. 3.5) and occurs at precisely twice the period, 7.8 hr.

by significant secondary minima which are an artifact of the data sampling (Gray and Desikachary 1973). The minima are separated by 1 cycle per day which is due to the 24 hr interval between each night's ~ 4 hr observing window. If terms in 2ω are included in the fit, the minimum value of χ_ν^2 is reduced somewhat and occurs at a period of 7.8 hr, precisely twice the most probable period mentioned above (see Fig. 2*b*). The fitted function has two equal minima and two unequal maxima (which differ by 0.08 mag) per period. If terms in 3ω and higher are included in the fit, the results are the same as those shown in Figure 2*b*.

The fitted intensity for the fundamental term only ($P = 3.9$ hr) is given by the expression,

$$I(\mathrm{ADU}/900\ \mathrm{s}) = 1740(\pm 12) + 135(\pm 18)\sin\left[\frac{2\pi(t - t_0)}{0.161(\pm 0.002)}\right],$$

where t and t_0 are in days and t_0 occurs at $8^{\mathrm{h}}15^{\mathrm{m}}(\pm 5^{\mathrm{m}})$ UT on 1981 November 1. (The time of minimum is a quarter of a cycle or 58 minutes earlier). The expression is plotted in Figure 1 as a smooth curve. It is apparent that the model is an imperfect fit to the data, which suggests that there may be additional variability (e.g., aperiodic or very long period variability) in the A0620−00 system.

III. DISCUSSION

In this section, we discuss four mechanisms which might produce the observed variability in A0620−00 and rule against a fifth mechanism which appears to be unlikely. In the following discussion, we assume that the 7.8 hr period discussed above is the orbital period.

a) *Ellipsoidal Light Variations*

It is possible that we have observed ellipsoidal light variations of the K dwarf caused by the tidal forces of the neutron star. Light curves of precisely this type have been observed in the dwarf novae EM Cyg and U Gem in the near-infrared (Jameson, King, and Sherrington 1981; Panek and Eaton 1982). An expression for the full amplitude of the ellipsoidal variations in terms of the system parameters is given by the formula (Russell 1945),

$$\Delta m(\mathrm{mag}) \approx \frac{3}{2} q f^3 (R/a)^3 \sin^2 i (1 + \tau_0) \frac{15 + u}{15 - 5u},$$

where $q = M_x/M_{\mathrm{opt}}$ is the mass ratio, $R/a \approx 0.38 - 0.2 \log q$ is the ratio of the Roche lobe radius of the K star to the distance between the stars (e.g., see Warner 1976), f is the radial fraction of the Roche lobe which is filled, and i is the orbital inclination angle. The gravity-darkening coefficient, τ_0, and limb-darkening coefficient, u, depend on the mean effective temperature and surface gravity of the star. If we approximate the spectrum of a K5 dwarf by a 4000 K blackbody, we find $\tau_0 = 0.57$ (Lucy 1967).[2] For a 4000 K stellar atmosphere with $\log g = 4.0$, we find $u \approx 0.85$ (Carbon and Gingerich 1969). Consequently, the light curve is a function of three independent parameters, q, f, and $\sin i$. If we adopt $M_x \sim 1.4\ M_\odot$ (Rappaport and Joss 1981), $f \sim 1$ (condition for effective mass transfer), and $i \sim 90°$ (double-peaked Balmer emission observed by Whelan *et al.* 1977 and Murdin *et al.* 1980), we find that the expected full amplitude of the variations for a K5 star is $\Delta m \approx 0.23$ which is consistent with the observations.[3] A maximum variability of 0.28 mag was observed

---

[2] Meridional currents beneath the photosphere may reduce the effects of gravity darkening (Kopal 1959).

[3] The expected amplitude for the A0620−00 system is somewhat less than 0.23 mag because the disk contributes a significant fraction of the total light (Oke 1977).

on the nights of November 2 and 3, and the full amplitude of the fit to all the data is 0.16 mag (Fig. 1).

b) *Eclipse Light Curve*

It is possible that we have observed an eclipse light curve which involves the K star and the accretion disk. It is difficult to quantify this model because it depends on the largely unknown geometry and temperature profile of the disk. Nevertheless, this is an attractive hypothesis because there is evidence that the orbital inclination of the system is large (Whelan *et al.* 1977; Murdin *et al.* 1980) and it is likely that the star and the disk are of comparable size (Robinson 1976). An eclipse light curve should have significantly greater color variations than an ellipsoidal light curve, and it may be possible to distinguish between them in future multicolor observations.

c) *Hot Spot*

The light curves of dwarf novae in quiescence frequently have prominent humps which may last for half an orbital period. The hump is generally attributed to a hot spot on the outer edge of the accretion disk which is produced by the impact of a stream of accreting gas (Warner 1976; Robinson 1976). The luminosity of the hot spot is typically $M_V \sim 7.5$ (Warner 1976), which is the same as the luminosity of the K5 secondary in A0620$-$00. Spectra of A0620$-$00 in quiescence show that the system contains an accretion disk which appears to be very similar to those observed in dwarf novae (Murdin *et al.* 1980). Moreover, the disk in A0620$-$00 contributes a significant fraction of the total emission in the $B + V$ passband (Oke 1977; Murdin *et al.* 1980). Is the mass accretion rate high enough to produce a significant hot spot on the disk? The energy release observed in the 1975 outburst of A0620$-$00 ($\sim 3 \times 10^{44}$ ergs) implies that the average mass transfer rate between the 1917 and 1975 outbursts was $\sim 3 \times 10^{-11}$ $M_\odot$ yr^{-1}.[4] This is within the range of mass transfer rates inferred for dwarf novae in quiescence (Tylenda 1981, and references therein), and it is therefore possible that the light curve is due to a hot spot on the accretion disk.

d) *Star Spots*

A fourth possibility is that the light curve is due to star spots on the K star which is rapidly rotating at the orbital period. This behavior is observed in RS CVn stars and BY Dra stars (e.g., see Eaton and Hall 1979; Bopp *et al.* 1981)

e) *X-Ray Heating*

A few X-ray binaries (e.g., Her X-1 and 4U 2129+47) have large-amplitude optical light curves which are due to optical radiation emitted from the X-ray–heated face of the companion star, which is modulated by changing aspect. The light variations we have observed in A0620$-$00 cannot be explained by this mechanism. Four years after the 1975 outburst, the X-ray luminosity of A0620$-$00 was less than 10^{32} ergs s^{-1} for an assumed thermal bremsstrahlung spectrum with $kT \sim 1$ keV (Long, Helfand, and Grabelsky 1981).[5] A K5 dwarf which fills its Roche lobe would intercept about 2.5% of the (isotropic) X-ray flux emitted by the neutron star. (The fraction may be even less if the optical companion is shielded by the accretion disk.) For an X-ray albedo of ~ 0.3 (Milgrom and Salpeter 1975), one hemisphere of the star would absorb $\lesssim 1.8 \times 10^{30}$ ergs s^{-1}, which corresponds to $\lesssim 0.30\%$ of the bolometric luminosity of a K5 dwarf. If we approximate the heated hemisphere by a flat disk which is illuminated uniformly by the X-ray source, then the temperature difference between the heated and the unheated hemispheres is $\lesssim 10$ K, and the corresponding full amplitude of the 4000–6400 Å light curve is $\lesssim 0.015$ mag. The amplitude which we observed is an order of magnitude larger, which rules strongly against the X-ray heating model.

IV. CONCLUDING REMARKS

In closing, we speculate on the origin of a 7.8 *day* periodicity in the X-ray and optical fluxes of A0620$-$00 which commenced about 5 months after the 1975 August outburst and lasted several cycles (Matilsky *et al.* 1976; Chevalier, Ilovaisky, and Mauder 1976). In Her X-1, the 35 day X-ray period is believed to be due to the precession of the accretion disk (Katz *et al.* 1982, and references therein). The ratio of the precession period to the orbital period is 20.5. For LMC X-4, this ratio is 21.8 (Lang *et al.* 1981), and for SS 433 it is 12.5 (Katz *et al.* 1982). For A0620$-$00, the ratio of the 7.8 day period to the 7.8 hour orbital period is 24. This suggests that the 7.8 day period, which was observed in the late decline phase of A0620$-$00, may have been due to the precession of the accretion disk.

The authors are grateful to Mark Bautz and Steven Meyer for help with the CCD instrumentation, Douglas Mink for providing data analysis software, Barry Klinger for assistance with the data analysis, and Matt Johns for technical assistance at the observatory. This work was supported in part by National Science Foundation grant AST 81-15557.

---

[4] We have assumed that mass transfer occurs during quiescence (Meyer and Meyer-Hofmeister 1981, and references therein). We have also assumed that no additional outbursts occurred between 1917 and 1975 (see Eachus, Wright, and Liller 1976).

[5] The spectrum was derived during the decline of the nova. For $kT = 3$ keV, for example, the limit on the luminosity is a factor of 2 higher.

REFERENCES

Boley, F., Wolfson, R., Bradt, H., Doxsey, R., Jernigan, G., and Hiltner, W. A. 1976, *Ap. J. (Letters)*, **203**, L13.

Bopp, B. W., Noah, P. V., Klimke, A., and Africano, J. 1981, *Ap. J.*, **249**, 210.

Carbon, D. F., and Gingerich, O. 1969, in *Theory and Observations of Normal Stellar Atmospheres*, ed. O. Gingerich (Cambridge: MIT Press), p. 377.

Chevalier, C., Ilovaisky, S. A., and Mauder, H. 1976, *IAU Circ.*, No. 2957.

Eachus, L. J., Wright, E. L., and Liller, W. 1976, *Ap. J. (Letters)*, **203**, L17.

Eaton, J. A., and Hall, D. S. 1979, *Ap. J.*, **227**, 907.

Elvis, M., Page, C. G., Pounds, K. A., Ricketts, M. J., and Turner, M. J. L. 1975, *Nature*, **257**, 656.

Gray, D. F., and Desikachary, K. 1973, *Ap. J.*, **181**, 523.

Jameson, R. F., King, A. R., and Sherrington, M. R. 1981, *M.N.R.A.S.*, **195**, 235.

Kaluzienski, L. J., Holt, S. S., and Swank, J. 1980, *Ap. J.*, **241**, 779.

Katz, J. I., Anderson, S. F., Margon, B., and Grandi, S. A. 1982, *Ap. J.*, **260**, 780.

Kopal, Z. 1959, *Close Binary Systems* (New York: Wiley), p. 171.

Lang, F. L., *et al.* 1981, *Ap. J. (Letters)*, **246**, L21.

Long, K. S., Helfand, D. S., and Grabelsky, D. A. 1981, *Ap. J.*, **248**, 925.

Lucy, L. B. 1967, *Zs. Ap.*, **65**, 89.

Matilsky, T., *et al.* 1976, *Ap. J. (Letters)*, **210**, L127.

Meyer, F., and Meyer-Hofmeister, E. 1981, *Astr. Ap.*, **104**, L10.

Milgrom, M., and Salpeter, E. E. 1975, *Ap. J.*, **196**, 583.

Murdin, P., Allen, D. A., Morton, D. C., Whelan, J. A. J., and Thomas, R. M. 1980, *M.N.R.A.S.*, **192**, 709.

Oke, J. B. 1977, *Ap. J.*, **217**, 181.

Panek, R. J., and Eaton, J. A. 1982, *Ap. J.*, **258**, 572.

Rappaport, S., and Joss, P. 1981, in *X-Ray Astronomy with the Einstein Satellite*, ed. R. Giacconi (Dordrecht: Reidel), p. 123.

Ricker, G. R., Bautz, M. W., Dewey, D., and Meyer, S. S. 1981, in *Solid State Imagers for Astronomy*, *Proc. Soc. Photo-Opt. Instrum. Eng.*, **290**, 190.

Robinson, E. L. 1976, *Ann. Rev. Astr. Ap.*, **14**, 119.

Russell, H. N. 1945, *Ap. J.*, **102**, 1.

Tylenda, R. 1981, *Acta Astr.*, **31**, 127.

Warner, B. 1976, in *IAU Symposium 73, The Structure and Evolution of Close Binary Systems*, ed. P. Eggleton, S. Mitton, and J. Whelan (Dordrecht: Reidel), p. 85.

Whelan, J., *et al.* 1977, *M.N.R.A.S.*, **180**, 657.

J. E. McClintock, L. D. Petro, R. A. Remillard, and G. R. Ricker: Massachusetts Institute of Technology, Room 37-521, 77 Massachusetts Avenue, Cambridge, MA 02139