1987RMxAA..14..330C

Rev. Mexicana Astron. Astrof., **14**, 330-335 (1987)

PHOTOMETRIC OBSERVATIONS OF THE Be/X-RAY BINARY SYSTEM 2S0114+650 = LSI+65°010

L. Corral and G. Koenigsberger

Instituto de Astronomía
Universidad Nacional Autónoma de México, MEXICO

RESUMEN. Se discute la variabilidad en rayos x de la fuente 2S0114+650 en el contexto de resultados preliminares de observaciones fotométricas ópticas y la solución orbital del sistema binario encontrada por Crampton et al. (1985).

ABSTRACT. An interpretation for the x-ray variability of the Be/x-ray source 2S0114+650 is presented in the context of preliminary optical photometric observations and the orbital solution for the binary system derived by Crampton et al. (1985).

Key words : STARS-BE -- STARS-BINARY -- STARS-X-RAY

INTRODUCTION

The Be/x-ray binary systems are low luminosity x-ray sources as compared to the classical, "massive" x-ray binaries (see review by Rappaport and van den Heuvel, 1981). In general, they consist of a main-sequence B-star and a collapsed companion believed to be a neutron star (NS). The x-rays are powered by wind accretion, which accounts for the relatively low x-ray luminosities.

The Be/x-ray sources are, as most x-ray sources, variable. One of the interesting problems related to these systems is to determine whether the x-ray variations can be correlated with optical variability, since:

a) an optical component is expected to arise near the accreting collapsed companion due to reprocessed x-rays, and
b) x-ray variations due to variable accretion rates may be related to variable stellar mass loss rates, which in turn may result from stellar pulsations, or may be indicative of non-homogeneous stellar winds.

An analysis of x-ray variations can be used to derive the properties of the stellar wind. For example, White et al. (1983) have shown, on the basis of x-ray spectral variations, that the stellar wind of the optical counterpart of 4U1700-37 most likely contains inhomogeneities of the type predicted by Lucy and White (1980) for radiation pressure driven winds. In addition, they attribute the x-ray flickering to the presence of the inhomogeneities.

On the other hand, stellar winds of early type stars tend to be unstable in the sense that episodic, enhanced mass loss may occur (see for example, Henrichs et al. 1983). This will naturally result in x-ray luminosity variations correlated with these instabilities. Since these $\dot{M}_w$ fluctuations must be related to stellar properties (rotation, luminosity, pulsation, magnetic field?) one might expect that the timescale of the stellar variations may coincide with some of the x-ray variability timescales. Thus, optical monitoring of Be/x-ray sources can lead to interesting results.

In this paper we will attempt to identify the various mechanisms which may be responsible for the x-ray variability of the Be/x-ray source LSI+65°010 = 2S0114+650, based on the orbital solution for the binary system obtained by Crampton et al. (1985). We also present the results of preliminary optical photometric variations.

VARIABILITY OF 2S0114+650

An analysis of the x-ray properties of this source has disclosed variability on three timescales (Koenigsberger et al. 1983) which we loosely classify as follows:

1. Long term: a high and a low state separated by 5-6 days.
2. Medium term: Flares lasting >30 minutes which involve changes by a factor of $\sim$10 in the x-ray luminosity.
3. Short term: Flickering or a possible pulsar phenomenon on a $\sim$15 minutes timescale.

Long term variations

In the light of the Crampton et al. orbital solution for the binary system it is easy to show that, adopting an eccentric orbit, the long-term x-ray variability is related to orbital phase effects. That is, the time at which the x-ray source was below the limit of the OSO-8 detectors (Figure 5 Koenigsberger et al. 1983) coincides with apoastron passage. At the same time, the maximum occurs near periastron. Since x-ray luminosity associated with the collapsed companion depends upon the speed of the stellar wind being accreted, the observed levels of x-ray emission at different orbital phases provides information on the velocity law of the wind. We may, in principle, determine the relative wind speeds at periastron (r_p) and apoastron (r_a) in the following manner:

Assuming the simplest model for spherical wind accretion, the accretion rate can be written as (Bondi and Hoyle, 1944; Davidson and Ostriker 1973):

$$\dot{M}_{ac}(r) = \frac{G^2 M_{ns}^{\;2}}{r^2 V_{rel}^{\;4}(r)} \dot{M}_w \tag{1}$$

where

$$V_{rel}^{\;2}(r) = V_w^{\;2}(r) + V_{orb}^{\;2}(r) \tag{2}$$

On the other hand, the accretion rate is related to the observed x-ray luminosity by:

$$\dot{M}_{ac} = \frac{L_x R_{ns}}{\eta\, G M_{ns}} \tag{3}$$

Substituting 3 in 1 and solving for $V_{rel}^{\;2}(r)$ one finds

$$V_{rel}^{\;2}(r) = \left[\frac{\eta G^3 M_{ns}^{\;3} \dot{M}_w}{R_{ns}\; r^2 L_x(r)}\right]^{\frac{1}{2}} \tag{4}$$

If we assume that the stellar mass loss rate is constant on the average, we can construct the ratio of the relative velocity at periastron and apoastron:

$$\frac{V_{rel}^{\;2}(r_p)}{V_{rel}^{\;2}(r_a)} = \left[\frac{L_x(r_a)\; r_a^{\;2}}{L_x(r_p)\; r_p^{\;2}}\right]^{\frac{1}{2}} = Q \tag{5}$$

and using (2)

$$V_w^{\;2}(r_p) = Q\, V_w^{\;2}(r_a) + Q\, V_{orb}^{\;2}(r_a) - V_{orb}^{\;2}(r_p) \tag{6}$$

1987RMxAA..14..330C

Given the orbital solution of Crampton et al. and the x-ray properties we can find the values of $V_w(r_p)$ as a function of $V_w(r_a)$. In Table 2 we list the values of $V_w(r_p)$ as a function of $V_w(r_a)$ calculated using the parameters in Table 1. In column 3 of Table 2 the ratios of periastron and apoastron wind speeds are listed.

TABLE 1. Parameters used to derive wind speed at different phases

Parameter	Value adopted	on the basis of/reference
$L_x(r_a)$ (ergs s^{-1})	$<1.6 \times 10^{34}$	OSO-8 limit; 1
$L_x(r_p)$ (ergs s^{-1})	4.2×10^{34}	non-flare Einstein; 1
Period (days)	11.58	2
e	0.16	2
M^* ($M_\odot$)	18	2
M_{ns} ($M_\odot$)	1.4	
a ($R_\odot$)	58	$= 4.2\ (M^* + M_{ns})^{1/3}\ P^{2/3}$
r_p ($R_\odot$)	49	$= a(1 - e)$
r_a ($R_\odot$)	67	$= a(1 + e)$

References: 1 Koenigsberger et al. 1983
2 Crampton et al. 1985

TABLE 2: Wind speeds at apoastron and periastron

$V_w(r_a)$	$V_w(r_p)$	$V_w(r_p)/V_w(r_a)$
1000	890	0.89
900	795	0.88
800	700	0.87
500	402	0.80

It is interesting to calculate the ratio $V_w(r_p)/V_w(r_a)$ for a 15 $R_\odot$ star assuming velocity laws of the form predicted by radiation pressure driven winds (Castor et al. 1975):

$$\frac{V_w(r_p)}{V_w(r_a)} = \frac{V_\infty(1 - R^*/r_p)^{\frac{1}{2}}}{V_\infty(1 - R^*/r_a)^{\frac{1}{2}}} = 0.94$$

However, assuming a slower velocity law

$$V_w(r) = V_\infty(1 - R^*/r) \tag{7}$$

yields a ratio of 0.88. Furthermore, given (7) a wind terminal speed $V_\infty = 1200$ km s^{-1}, is obtained, if $V_w(r_a)$ is taken as 900 km s^{-1}

Clearly, this is the simplest approach to this problem. However, it illustrates that the neutron star most likely lies within the acceleration region of the Be star wind, and that the different wind speeds alone can account, to a first approximation, for the low and steady (non-flare) high x-ray states.

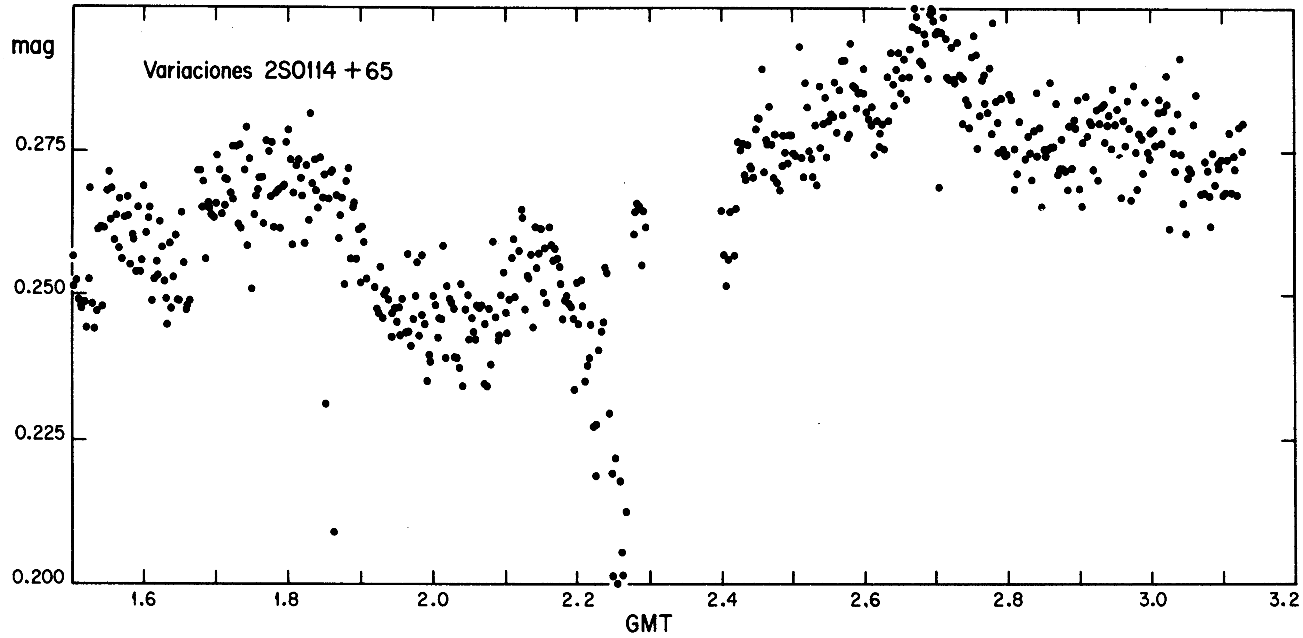

Fig. 1. Optical photometric observations of 2S0114 + 650. Each point represents a 10-second integration. Δm (mag) is plotted as a function of GMT (hours).

Medium Term Variations

The Einstein data (Figure 1 of Koenigsberger et al.) contain two flares, separated by ~6 hours. The orbital phase of this data is near periastron. Repetitive flaring activity is exhibited by other members of this class of sources (c.f., A0538-66, White and Carpenter 1978; Skinner et al. 1980). This phenomenon has been interpreted as resulting from the passage of the neutron star through the disk of material expelled by the rotating Be star. However, the estimated rotation speed of the optical component in 2S0114 + 650 is low (~100 km s^{-1}, Crampton et al.), making the presence of an equatorial disk unlikely. In addition, enhanced mass loss at the equator is also unlikely to provide an explanation of the flares. A larger $\dot{M}_W$ would simply raise the level of x-ray emission, since the x-ray luminosity is well below the Eddington limit.

Ignoring accretion instabilities related to magnetic fields, we consider a more likely explanation for the flares to be in terms of inhomogeneities in the stellar wind. These inhomogeneities can arise from at least two different mechanisms: shocks in the wind and episodic enhanced mass loss. The first of these arise in radiation pressure driven winds (Lucy and White 1980). But statistical fluctuations of these inhomogeneities are not expected to produce variations in the optical properties (Lucy 1983), and hence, should not be detectable photometrically. Episodic enhanced mass loss, on the other hand, must be related to the properties of the Be star, and may be related to variations in its luminosity.

In Figure 1 we illustrate the photometric behavior of LSI+65°010 on the night of 17 January 1986, corresponding to an orbital phase near apoastron. These data were obtained at the 1 meter telescope of the National Observatory in Tonantzintla, Puebla, with the Two-Star photometer, which allows simultaneous monitoring of source and comparison stars. The integrations were made every 10 seconds. No filters were used.

Evidence for variations on timescales comparable with those of the x-ray flares is present in these data. Thus, the flaring activity may be related to episodic enhanced mass loss, rather than filamentary shocks in the wind. However, simultaneous x-ray and optical observations are necessary in order to determine whether the rise in optical luminosity coincides with

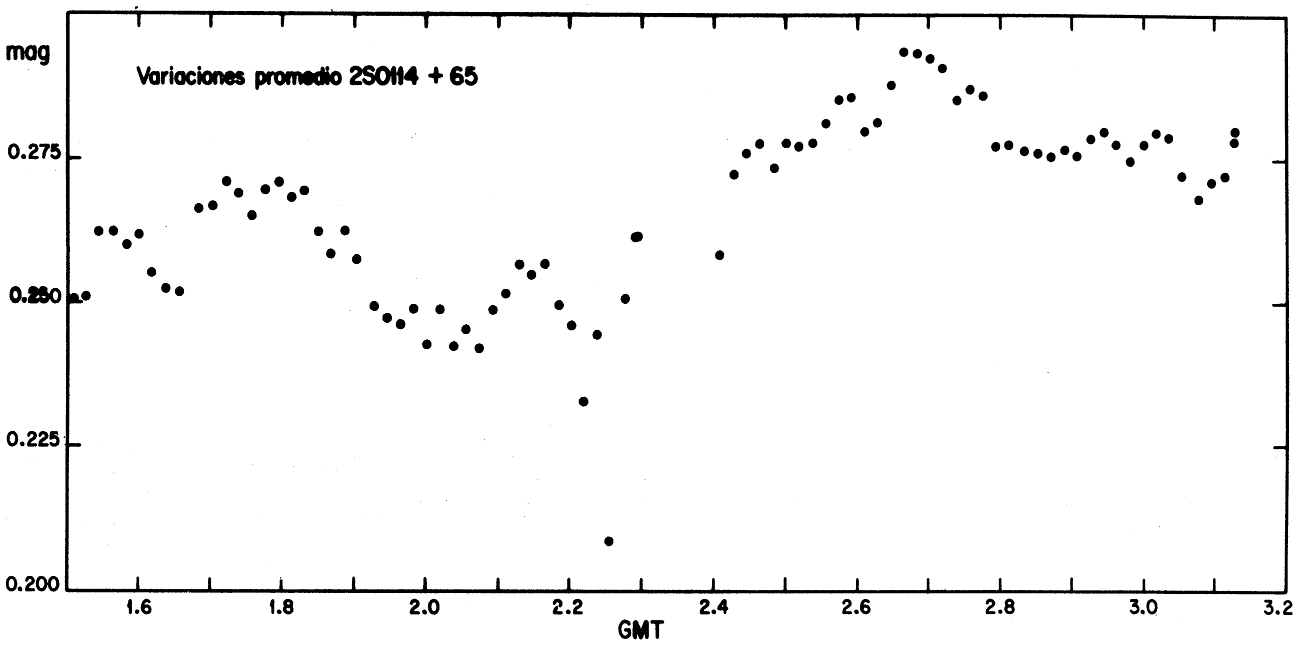

Fig. 2. Same as in Figure 1, but here each point represents a one-minute average.

that in x-rays or preceeds it, since the optical variations may be associated with reprocessed x-rays. In addition, a longer baseline of observations are required in order to determine whether this optical variability is periodic.

Short Term Variations

The variations in x-ray luminosity with a possible period of 14.9 minutes may be attributed to a pulsar phenomenon. If this is the case, we might ask whether optical variability due to reprocessed x-rays is expected. Unless the reprocessing region is small enough ($d = P_{pulse} * c$), optical pulsations modulated with the x-ray pulse period will not be observable. Other Be/x-ray systems have been studied with the aim of detecting optical pulsations with no success (e.g. Hutchings and Walker 1976; Margon et al. 1977; Wade and Oke 1977; Bernacca et al. 1984; Corbet et al. 1985). Assuming P_{pulse} = 14.9 minutes in 2S0114+650, $d = 2.7 \times 10^{13}$cm, which is nearly an order of magnitude larger than the orbital separation. Hence, this may be a good candidate for searching for modulated optical variations on this time scale. In Figure 2 we illustrate the one-minute averages of our photometry, where 0.01 magnitude changes are visible with timescales of $\sim$10 minutes, but clearly, our data are not sufficient to check for periodicity.

CONCLUSIONS

We find that the long term x-ray variations reported by Koenigsberger et al. (1983) are consistent with varying accretion rates onto the collapsed companion due to an eccentric orbit, as derived by Crampton et al. (1985). Furthermore, we conclude that the orbit of the collapsed companion most likely lies within the accelerating region of the wind.

Preliminary optical photometric observations suggest that the x-ray flaring activity may be associated with luminosity variations of the Be star, leading to episodic enhanced mass loss. However, optical variability due to reprocessed x-rays is also a feasible interpretation, and thus simultaneous optical and x-ray observations are highly desirable.

ACKNOWLEDGEMENT

We thank A. García for the figures and J.F. Barral for computing assistance.

REFERENCES

Bernacca, P.L., Iijima, T., Stagni, R. 1984, *Astron. Astrophys.*, 132, L8.
Bondi, H. and Hoyle, F. 1944, *M.N.R.A.S.*, 104, 273.
Castor, J.I., Abbott, D.C., Klein, R.I. 1975, *Astrophys. J.*, 195, 157.
Corbet, R.H.D., Mason, K.O., Cordova, F.A., Branduardi-Raymond, G., Parmar, A.N. 1985, *M.N.R.A.S.* 212, 565.
Crampton, D., Hutchings, J.B., Cowley, A.P. 1985, *Astrophys. J.*, 299, 839.
Davidson, K. and Ostriker, J. 1973, *Astrophys. J.*, 179, 585.
Henrichs, H.F., Hammerschlag-Hensberge, G., Howarth, I.D., Barr, P. 1983, *Astrophys. J.*, 268, 867.
Hutchings, J.B. and Walker, G.A.H., 1976, *P.A.S.P.*, 88, 754.
Koenigsberger, G., Swank, J.H., Szymkowiak, A.E., White, N.E. 1983, *Astrophys. J.*, 268, 782.
Lucy, L.B. 1983, *Astrophys. J.*, 274, 372.
Lucy, L.B., White, R.L. 1980, *Astrophys. J.*, 241, 300.
Margon, B., Nelson, J., Chanan, G., Thorstensen, J.R., Bowyer, S. 1977, *Astrophys. J.*, 216, 811.
Rappaport, S. and van den Heuvel, E.P.J. 1981, in *IAU Symposium No. 98 on Be Stars*, N. Jaschek and H.G. Groth (eds), p. 327.
Skinner, *et al.* 1980, *Astrophys. J.*, 240, 619.
Wade, R.A., Oke, J.B. 1977, *Astrophys. J.*, 215, 568.
White, N.E. and Carpenter, G.F. 1978, *M.N.R.A.S.*, 183, 11P
White, N.E., Kallman, T.R., Swank, J.H. 1983, *Astrophys. J.*, 269, 264.

L. Corral and G. Koenigsberger: Instituto de Astronomía, UNAM, Apartado Postal 70-264, México
D.F. 04510, México.