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LETTER

Letter to the Editor

Is Her X-1 really strange?

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Abstract. It has recently been proposed that the compact accreting object in the well-studied X-ray binary Hercules X-1 is not a neutron star at all, but a strange star; *ie* one composed of bulk quark matter. This conclusion has been arrived at by comparing a semi-empirical mass-radius (*M-R*) relation for Her X-1 with theoretical *M-R* curves for neutron and strange stars, and showing that the strange-star models are favoured. However we argue that other data in the literature, and recent observational results (namely new mass and distance estimates) suggest that the hypothesis that Her X-1 is a normal neutron star is not disproved.

Key words: stars:individual:Hercules X-1 – stars:neutron – stars

1. Introduction - Her X-1

Hercules X-1 is a well-studied X-ray binary consisting of an accreting pulsar rotating once every 1.24 s, in a 1.7 d orbit around the 2.0 $M_\odot$ star HZ Her. Although there are many unsolved problems relating to this system, the nature of the compact object (hereafter referred to as Her X-1) has seemed clear since the binary's discovery (Tananbaum et al 1972): there are a large number of indications that it is a rotating, highly magnetized neutron star. These include the shape of the X-ray spectrum, the high surface magnetic field strength (B $\approx 10^{12}$ G) implied by the 35 keV cyclotron feature, and the mass, estimated by various authors to lie in the range ~ 1 — 1.5 $M_\odot$.

However, Li et al (1995) have recently made the suggestion that the compact object might be a strange star. If this were the case, Her X-1 would be the first such object identified. However, Li et al's conclusion is dependent on several observed parameters; in particular the mass and the distance (and hence luminosity) of the system. Since both these parameters have recently been redetermined (Reynolds et al 1997), and differ considerably from those used by Li et al, a reassessment of the strangeness argument seems valid.

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2. The case for Her X-1 being a strange star

Following Wasserman & Shapiro (1983), Li et al (1995), hereafter L95, show how semi-empirical *M-R* relations may be derived from several external properties of X-ray pulsars: the pulse period, the rate of change of the pulse period, the luminosity, and the cyclotron line energy. These relations define curves on a plot of mass versus radius. If the *theoretical* relations for various equation-of-state models are also plotted, at least one should intersect the semi-empirical *M-R* relation. Ideally, it should do so at a point which lies within the error-bound of the object's observed mass. The essence of the argument given by L95 (see also Wassermann & Shapiro 1983) is - firstly - that of the three theoretical *M-R* curves for neutron stars which are considered, *none* intersect the semi-empirical curve unless the luminosity is assumed to be much higher (near the Eddington limit) than the generally assumed value of 2.0×10^{37} ergs s^{-1}. Secondly, L95 argue that the most realistic theoretical curve (the one with the stiffest equation of state) never intersects, even in the Eddington case. Thirdly - although not explicitely stated by L95 - even if the luminosity were higher (i.e., if the distance would have been underestimated), the points of intersection are too high to be compatible with the observed mass range which L95 plot on the same figure.

By contrast, L95 show that the case for the strange-star models is better; they plot three equation-of-state curves characterised by different "bag constants"; if the constant is 200 MeV, then there is good agreement between the semi-empirical and theoretical curves, without requiring a higher luminosity. Of particular note is the fact that the upper limit to the mass given by the best strange model is ~ 1.1 $M_\odot$, which is just compatible with the upper error on the observed mass.

Before discussing how data other than that used by L95 may lead to a different conclusion, the possibility of substantial systematic errors in the results obtained from the application of the Wassermann & Shapiro (1983) method should be addressed. The method depends on a model for the accretion torque (that of Ghosh & Lamb, 1979), which makes the assumption that the B-field is exactly dipolar and aligned with the pulsar's rotational axis. L95 use a different description of the accretion torque (that of Li & Wang 1995), but make the same simplifying assumptions, at least the second of which is known to be wrong, or else the star would not be a pulsar. These simplifications, and other uncertainties, may lead to large systematic errors in the semi-empirical *M*-*R* relationships. Even though L95 argue that the semi-empirical curves are insensitive to the underlying torque model, some skepticism must be in order before any conclusions are drawn from this technique.

Nonetheless, we argue that even if the technique is valid, its application to Her X-1 is open to a different interpretation than that of L95. This lies in the choice of observed parameters which the authors use. While they consider the case that the luminosity might be much higher, they do not address the uncertainty in the observed mass. There are three commonly-cited estimates of the mass of the compact object; two via spectroscopic radial-velocity studies (Koo & Kron 1977; Hutchings et al 1985), and one which was based on timing studies of the optically-reprocessed X-ray pulses (Middleditch & Nelson 1976). L95 adopt the Hutchings et al result, which is by far the lowest, with M = 0.93 $\pm$ 0.07 $M_\odot$.

3. The implications of the newest mass and distance estimate

The new mass estimate derived by Reynolds et al (1997) is M = 1.5 $\pm$ 0.3 $M_\odot$, based on a recent spectroscopic radial velocity study of Her X-1's companion star HZ Her. This is incompatible with the Hutchings et al (1985) result, but consistent with the estimate of Koo & Kron (1977; $M \sim 1.5$ $M_\odot$), and Middleditch & Nelson (1976; M = 1.3 $M_\odot$). Furthermore, the latter result is based on timing of the optically-reprocessed X-ray pulsations, and so may be less susceptible to the systematic errors which plague radial velocity studies. In the light of these results, we believe that the argument of L95 should be reexamined with a lower mass limit for the pulsar of no less than 1.2 $M_\odot$).

Reynolds et al (1997) also provide a new distance estimate. This is obtained by using the new mass estimate to evaluate the size of the Roche-filling companion, together with a recently-determined T_{eff} for the unheated face (Cheng et al 1995), and appropriate values for E(B-V), the Bolometric Correction and the observed V band photometric magnitude of the unheated face. The resulting distance is d = 6.6 $\pm$ 0.4 kpc. L95 use a luminosity of L_X= 2.0 $\times$ 10^{37} ergs s^{-1} for d=5.0 kpc; if the newer estimate is correct, L_X would have to be revised upward by a factor of $\sim(6.6^2/5.0^2) = 1.8$; giving L_X=3.5 $\times$ 10^{37} ergs s^{-1}. Howarth and Wilson (1983) favour d = 6.0 kpc, which would also imply a higher L_X.

These two results invite a redrawing of the basic figure used in L95's argument. This revision is shown in Fig 1. The semi-empirical *M*-*R* relations are generated by solving numerically equations (1) — (5) from L95. For consistency we plot the

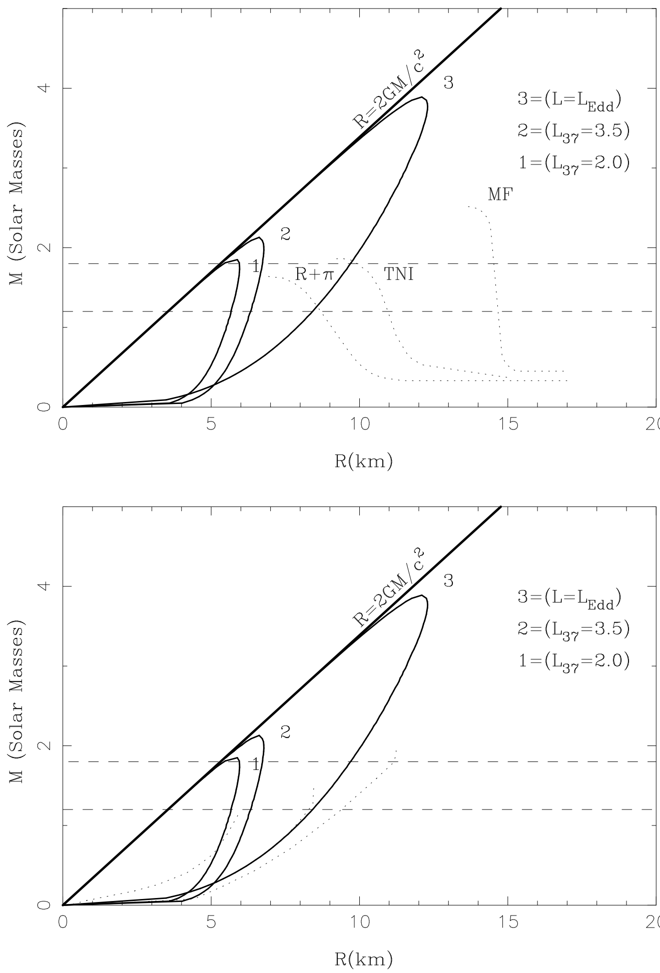

Fig. 1. Mass-Radius constraints for Her X-1. The Figure follows the scheme of Wassermann & Shapiro (1983) and L95; all stationary objects to the left of the thick line are within their own Schwarzchild radius and so are Black Holes. The upper box shows the semi-empirical *M-R* curves for Her X-1, with assumed luminosities of L_X = 2.0 $\times$ 10^{37} ergs s^{-1} (curve labelled '1'), L_X = 3.5 $\times$ 10^{37} ergs s^{-1} (curve '2') and the case where the luminosity is Eddington (curve '3'). The observed constraints on the mass are given by the two horizontal dashed lines. The dotted curves indicate the theoretical *M-R* curves for three different neutron-star equation-of-state models, which have been reproduced from the curves given by L95 and Wassermann & Shapiro (1983). The lower box is the same, except that the equation-of-state models are for strange stars. From left-to-right they are for bag constants of 200, 175 and 145 Mev; reproduced from L95.

curves for luminosities of L_X=2.0 $\times$ 10^{37} ergs s^{-1} and L_X=L_{Edd}, using the same input parameters as L95; visual inspection indicates that these curves are identical with those plotted in L95. We also plot the case L_X=3.5 $\times$ 10^{37} ergs s^{-1}, which results in an intermediate curve, which we believe is the most realistic solution. In place of the range of possible masses which L95 plot, based on the Hutchings et al estimate, we plot the range according to the estimate of Reynolds et al (1997); 1.2 — 1.8 $M_\odot$. The *theoretical M-R* curves, which do not change with the new results, have been reproduced from L95 and Wassermann & Shapiro (1983).

Discussing first the upper box of Fig. 1, the model which comes closest to intersecting the L_X=2.0 × 10^{37} curve is the $R + \pi$ curve, as noted by L95. The discrepancy is large, but is significantly reduced if the revised luminosity estimate is adopted, and becomes negligible if Her X-1 is assumed to lie at the upper-end of the revised distance estimate. There would therefore be no reason for rejecting the hypothesis that Her X-1 is a neutron star.

Turning to the lower box of Fig. 1, the case for Her X-1 being a quark star is weakened by the revised mass-estimate. Although, as L95 note, the curve for a bag constant of 200 MeV does indeed intersect the L_X=2.0 × 10^{37} semi-empirical *M-R* relation, it does so below the permitted mass-range. The case is improved if the luminosity is assumed to be intermediate between L_X = 2.0 and L_X=3.5 × 10^{37}, but the upper cutoff off the theoretical model would still be just below the allowed mass range.

4. Conclusions

L95 have suggested that the compact object in Her X-1 is a strange star. However their argument is dependent on both a low distance estimate and a low mass estimate. Apart from the fact that other, higher values for these parameters have already been published, recent work by Reynolds et al (1997) has further weakened the case for using the low values. This in turn weakens the argument of L95 on two fronts. Firstly, the discrepancy between the observation and theoretical *M-R* relations for the hypothesis that Her X-1 is a neutron star is reduced. Secondly, the converse hypothesis - that Her X-1 is a strange star - is weakened, since the theoretical curves no longer intercept the observational relations within the permitted mass range.

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