A MODEL FOR THE X-RAY BINARY 4U1820-30

Shigeki Miyaji[1,2]
Space Science Laboratory
NASA Marshall Space Flight Center

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[1]NAS/NRC Resident Research Associate
[2]On leave from Department of Natural History, College of Arts and Sciences, Chiba University, Chiba 260, Japan

ABSTRACT

Analysis of X-ray bursts from 4U1820-30 implies that the mass and radius of the neutron star are 1.4 $M_{\odot}$ and 8 km, respectively, and that the accreted material is hydrogen rich. On the other hand, the recently discovered orbital period of 685 seconds suggests that the companion is a degenerate star consisting mostly of helium. We show that apparent conflict can be resolved if the mass and radius of the companion are 0.08 $M_{\odot}$ and 2×10^9 cm, respectively, with a mean hydrogen concentration by weight of $\langle X \rangle = 0.1$. The possible origin of such a binary system is discussed.

Subject headings: stars:binaries - stars:neutron - X-rays:binaries - X-rays:bursts

I. INTRODUCTION

4U1820-30 was one of the first x-ray sources to be identified in a globular cluster (NGC6624; Giacconi et al., 1974) and to show X-ray bursts (Grindlay et al., 1976). New observations of this source have revealed that it also shows quasi periodic oscillations at frequencies 15-35 Hz (Stella, White, and Priedhorsky, 1986b) and has a very short orbital period of 685 seconds (Stella, Priedhorsky, and White, 1986a).

Recent observations of seven X-ray bursts from 4U1820-30 (Haberl et al., 1986) found double peaks in the hard X-ray burst profiles. Together with the evolution in luminosity and color temperature of bursts, this suggests that the material accreted onto the neutron star is hydrogen rich (see e.g., Sugimoto, Ebisuzaki, and Hanawa, 1984). On the other hand, the short orbital period suggests that the secondary is a degenerate helium star (Stella et al., 1986a) so that the accreted material is pure helium.

The purpose of this paper is to carefully study the X-ray bursts and period observations and to suggest a possible resolution of the apparent contradiction posed above. In Section II we analyze the EXOSAT observation of X-ray bursts from 4U1820-30 in order to obtain the mass and radius of the neutron star using commonly accepted models and to constrain the hydrogen abundance in the accreted material. In Section III we discuss the nature of the companion star. In Section IV we propose a consistent model for the binary system. Concluding remarks are given in Section V.

II. ANALYSIS OF X-RAY BURSTS OBSERVATION

a) Neutron Star Mass and Radius.

Recently Haberl et al. (1986) observed seven double-peak bursts from 4U1820-30. Unfortunately, the detailed time evolution of each burst is not available, but by taking points from their figures we can draw a probable locus of the evolutionary track for these bursts in a luminosity-color temperature ($L-T_c$) diagram (Figure 1).

Since these luminous bursts show significant expansion of the envelope, we can assume that the maximum luminosity is the Eddington luminosity, L_{Edd}, given by

$$L_{Edd} = \frac{4\pi cG}{\kappa_e} \frac{M}{1+X} \left(1 - \frac{2G}{c^2} \frac{M}{R}\right)^{1/2} . \tag{1}$$

Here κ_e and X are the electron scattering opacity (0.2 $cm^2 g^{-1}$) and hydrogen concentration by weight, respectively, and the other symbols have their usual meanings. Together with this equation, the $L-T_c$ relation observed during the cooling phase (solid line of Fig. 1) allows us to determine the mass and radius of the neutron star for 4U1820-30.

According to the radiative transfer calculations for a neutron star atmosphere by Ebisuzaki (1986), there is a relation between the color temperature and the effective temperature, T_{eff}. This relation depends on the luminosity itself and, in the case of the Eddington luminosity, it is given by

$$T_c(L_{Edd}) = 1.60\ T_{eff}(L_{Edd}). \tag{2}$$

The value of $T_c(L_{Edd})$ is obtained by fitting the results of model atmosphere calculations (Ebisuzaki and Nomoto, 1986) to the observation. The best fit model is pure helium atmosphere which is shown by a solid line in Figure 1. On the other hand, T_{eff} is given by (Ebisuzaki, 1986)

$$T_{eff} = \left(\frac{cG}{\sigma\kappa_e} \frac{M}{(1+X)R^2}\right)^{1/4} \left(1 - \frac{2G}{c^2} \frac{M}{R}\right)^{3/8}. \qquad (3)$$

Substituting the values of $L_{Edd}(He) = 2.5 \times 10^{38}$ erg/sec and $T_c(L_{Edd}(He)) = 3.10$ keV into equations (1) - (3), we obtain the mass and radius of the neutron star are about 1.4 M_o and 8 km. These are plausible values for 4U1820-30 although slightly smaller than those found for X1636-53 by Ebisuzaki (1986).

b) Composition of the Accreted Material

Figure 1 also shows that the evolutionary track of the double-peak bursts during expansion is different from that during contraction. Furthermore, the luminosity of the expansion phase is approximately half that of the maximum luminosity during the contraction phase which we assume is the Eddington luminosity for pure helium. These facts indicate (Sugimoto et al., 1984) that the composition of the envelope changes between these two phases from hydrogen rich matter to pure helium.

The evolution of the bursts would be much different than observed if the envelope had uniform composition. The envelope expands only when the local luminosity, L, is very close to the Eddington luminosity ($1-L/L_{Edd} < 10^{-3}$; Paczynski and Anderson, 1986). Therefore, if the envelope consists of a single layer with uniform composition, the tracks of the expansion and contraction phases should be the same. Figure 1 shows that this is apparently not the case for the seven bursts observed from 4U1820-30 by Haberl et al. (1986).

We can measure the value of X by comparing the turn over luminosity in the L-T_c diagram (i.e., where the expansion takes place) to the saturated maximum luminosity (i.e., where contraction proceeds). More detailed observations and analysis are required to determine a precise value, but inspection of Figure 1 shows that X is 0.5-1.0. This estimate is very rough but sufficiently robust for us to conclude that the neutron star has a hydrogen rich layer atop the helium layer.

III. RESTRICTIONS FOR THE COMPANION STAR FROM ORBITAL PERIOD OBSERVATION

The power spectrum for the EXOSAT data from 4U1820-30 shows a distinct feature at 685 seconds (Stella et al., 1986a). Stella et al. (1986a) give compelling reasons for believing that this period is the orbital period, P, of the binary. If we assume that it is an orbital period and that mass transfer takes place by Roche lobe overflow, we can tightly constrain the nature of the companion star. Because it is in the globular cluster, the companion mass should be smaller than 0.8 M_o if it is a non-degenerate star (turn off mass of NGC6624; Verbunt, 1986) and smaller than the Chandrasekhar mass (1.46 M_o) if it is a compact star. Therefore the total mass of the system should be smaller than 2.9 M_o so that the separation $d < 1.7 \times 10^{10}$ cm. Thus, the companion star should be compact.

Because the persistent X-ray luminosity, and therefore the mass transfer rate, is high (Stella et al., 1986a), the companion star should be just filling its Roche lobe. Combining the Keplar's law with the Roche lobe radius relation given by Paczynski (1971) we obtain an equation relating the mass, M_c, and the radius, R_c, of the companion star to the orbital period given by

$$(R_c/\mathrm{cm})^3/(M_c/M_o) = 3.32 \times 10^{23}\ (P/\mathrm{sec})^2. \qquad (4)$$

The structure of a zero temperature degenerate star is well approximated by a polytrope with index 1.5. Using the equation of the state for non-relativistic electrons, the mass-radius relation for such a degenerate star is given by

$$(M/M_{\odot})(R/cm)^3 = 6.75 \times 10^{26} (1+X)^5. \quad (5)$$

We can not apply this equation for masses larger than the critical value such that the cental temperature exceeds the nuclear ignition temperature during its gravitational collapsing stage. This critical value is 0.08 and 0.25 $M_{\odot}$, for X = 0.73 and 0.0, respectively (see e.g., Arnett, 1978).

In Figure 2, equations (4) and (5) are plotted using the observed orbital period of P = 685 seconds (Stella et al., 1986a). The possible parameter ranges for M_c and R_c are shown as the solid part of the line for equation (4).

IV. THE NATURE AND EVOLUTION OF THE COMPANION STAR

From studies of single star evolution, intermediate concentrations of hydrogen in a white dwarf are unlikely. The mass of a helium white dwarf in NGC6624 should be greater than 0.2 $M_{\odot}$, corresponding to the turn off mass 0.8 $M_{\odot}$. Therefore the present mass for helium white dwarf companion (0.06 $M_{\odot}$; Stella et al., 1986a) should be a result of mass transfer (mass loss) from the white dwarf. If the companion star evolved in this way, then its envelope must be pure helium now. However the material accreted onto the neutron star seems to contain a significant amount of hydrogen (see Section II-b). Therefore, this scenario is not plausible for the X-ray source 4U1820-30.

However, if the companion evolved as a binary component, then intermediate concentrations of hydrogen in the degenerate companion star are possible. In this scenario, the 4U1820-30 system would be the product of a tight binary containing an evolved main-sequence star and a neutron star or a white dwarf. Such a system could be formed by three body interaction or by common envelope evolution. When the main-sequence star has lost a large fraction of its mass down to less than 0.08 $M_{\odot}$ either via mass transfer to the compact primary or by sweeping away the common envelope by the supernova explosion when the white dwarf collapses into a neutron star (see e.g., Cameron and Iben, 1986), hydrogen burning in the main-sequence star would be extinguished and the ex-main-sequence star cools to become a degenerate star. Then the degenerate star would have an intermediate concentration of hydrogen. Since a composition gradient

($dX/dM_r \sim 4$) already exists in the center of an evolved main-sequence star, penetration of surface convection to the center is not expected (Tutukov et al., 1986). Therefore, the structural mean molecular weight of electrons $\langle 2/(1+X) \rangle$ in the degenerate star is higher than the molecular weight in the outer layers.

Substituting $M = 0.08\ M_{\odot}$ and $P = 685$ seconds into equations (4) and (5), we have $\langle 1+X \rangle \lesssim 1.1$. This value is lower than the value obtained in Section II-b but is at least of the same order of magnitude. Considering the distribution of hydrogen inside the star, it is likely that X is larger than 0.1 in the accreted material, especially if we adopt a value for $\langle X \rangle$ near the upper limit of 0.1.

Therefore a consistent model for the observations of 4U1820-30 is a binary system consisting of a neutron star ($M_{ns} = 1.4\ M_{\odot}$ and $R_{ns} = 8$ km) and a degenerate star ($M_c = 0.08\ M_{\odot}$, $R_c = 2 \times 10^9$ cm, and $\langle X \rangle = 0.1$).

V. DISCUSSION

There are many uncertainties concerning both the observations and the theoretical models. However, X-ray observations of 4U1820-30 provide a critical probe of X-ray burst models and of scenarios for the formation and evolution of X-ray binaries. We offer a few remarks here.

The color temperature in the early phase of the bursts has large observational uncertainties which tend to obscure the difference in the hydrogen and helium Eddington luminosities for each burst. However six out of seven bursts show about a factor of 1.5 lower luminosity at the time of maximum expansion. The difficulties in determining the temperature may also lead to the super Eddington points in Figure 1. More detailed analysis of the data is needed. If observation of the cooling phase of less luminous (no mass loss) bursts is available, we can also determine the hydrogen abundance ratio by fitting to a hydrogen rich atmosphere.

Further study of the 685 seconds period is necessary. To examine other possibilities (e.g., rotational period, orbital period of hot spot on the accretion disk, etc.), a detailed history of period changes and more detailed knowledge of the dependence of the light curve on energy are required.

Further theoretical work on the scenario given above for producing a degenerate star with an intermediate concentration of hydrogen is required. Especially critical is a detailed investigation of the processes that extinguish hydrogen burning.

A detailed study of the models for double peak burst is needed. The difference in the evolutionary track of a double peak burst might be caused by structural changes in the envelope. The rapid rotation of the neutron star (a reasonable assumption for evolutionary reasons) causes a transverse doppler shift (Fujimoto, 1985) which must be included for determining the effective temperature.

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FIGURE CAPTIONS

Fig. 1. The luminosity-color temperature diagram of seven bursts observed by Haberl et al. (1986). The evolutionary track of bursts is indicated by different marks corresponding to the time sequence. Dashed lines indicate corresponding Eddington luminosities for X = 0.0 and 0.73. Solid line shows best fit atmosphere model. This figure was constructed by reading from Figs. 3 and 4 of Haberl et al. (1986).

Fig. 2. Possible parameter ranges (thick solid line) of a degenerate secondary component based on eqs. (4) and (5) which are dash-dotted and dotted lines, respectively. For comparison, mass-radius relations of hydrogen and helium main-sequences are also shown.

Author's Address:

SHIGEKI MIYAJI: ES65, NASA Marshall Space Flight Center,
Huntsville, AL 35812

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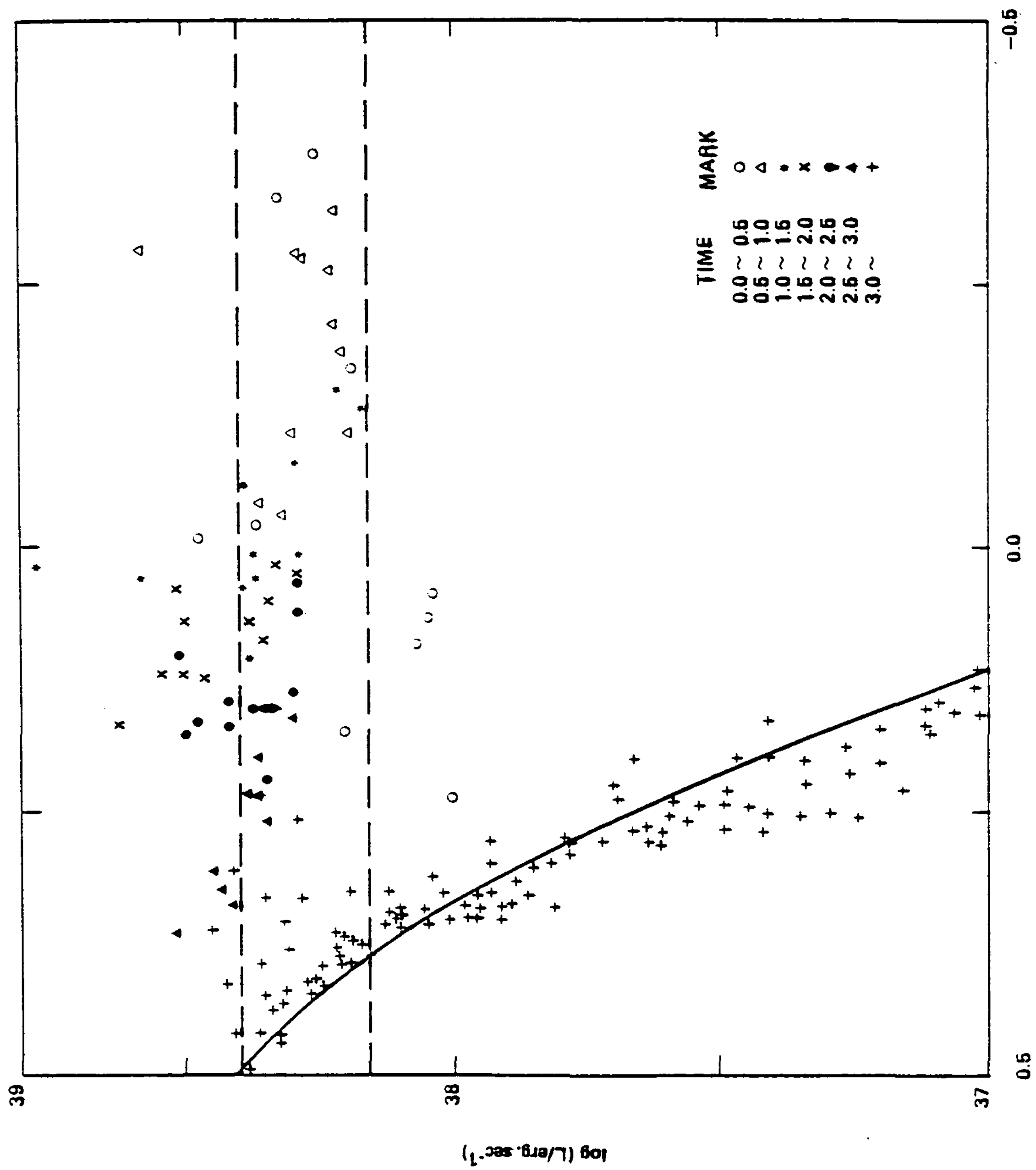
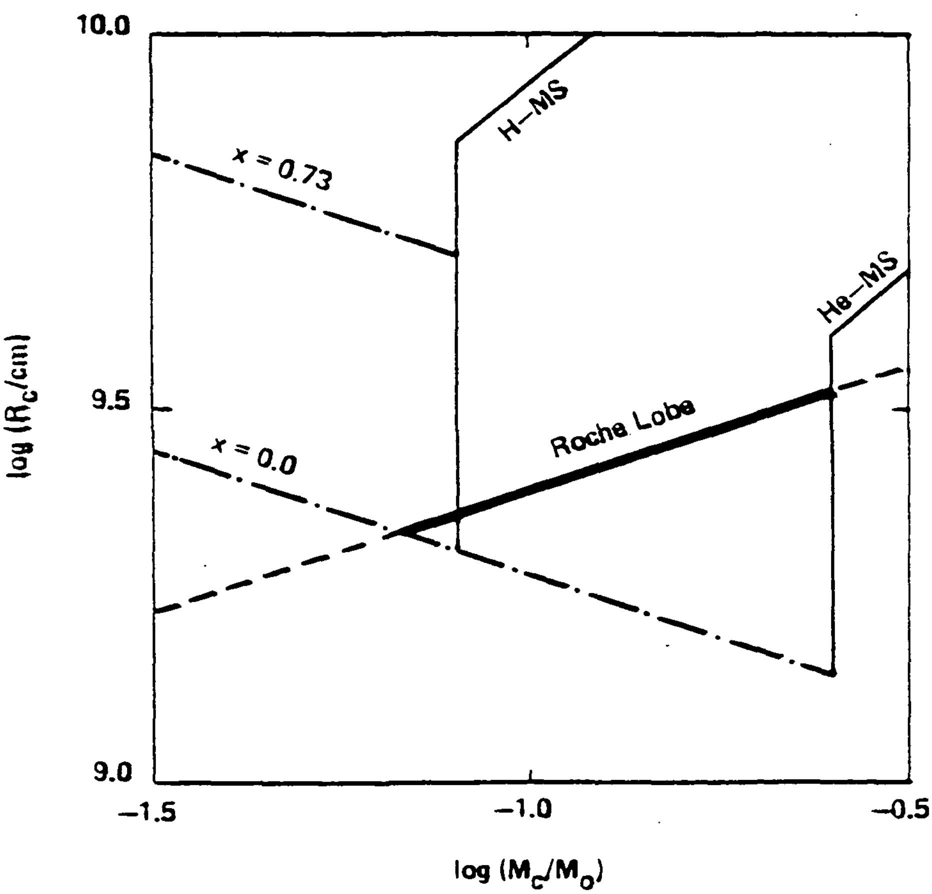


Figure 1



10.0
9.5
9.0
log (R_c/cm)
−1.5
−1.0
−0.5
log (M_c/M_O)
H–MS
He–MS
x = 0.73
x = 0.0
Roche Lobe

Figure 2