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ARE THE COMPACT X-RAY SOURCES DIFFERENTIALLY ROTATING DEGENERATE DWARFS?

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ABSTRACT

Many compact X-ray sources have been found to be members of close binaries. A class of models in which the X-ray source is taken to be a differentially rotating, degenerate dwarf is discussed. Such an object may be a natural result of stellar evolution in close binaries. Variants of the basic model can account for the different observed types of X-ray sources and provide semiquantitative explanations of the observed X-ray luminosities and of the spinup of the pulsating sources. In addition, the model makes some predictions that render it particularly susceptible to observational test.

Subject headings: binaries — black holes — rotation, stellar — X-ray sources

I. INTRODUCTION

Observations by the X-ray satellite *Uhuru* have led to the discovery of more than 50 galactic compact X-ray sources, many of which have been found to be members of eclipsing binary systems (Gursky 1972). At least two of these binary sources exhibit regular X-ray pulsations with periods in the range of 1–5 seconds (Her X-1: $P_{\text{Her X-1}} =$ 1.24 s [Tananbaum *et al.* 1972*b*]; Cen X-3: $P_{\text{Cen X-3}} = 4.87$ s [Giacconi *et al.* 1971]). The pulsation periods of these two sources have also been found to *de*crease on a time scale $\sim 10^5$ years (Tananbaum 1972). At the same time, optical, radio, and X-ray observations have provided strong evidence that Cyg X-1 is a member of the close binary system containing the star HDE 226868 (Webster and Murdin 1972; Bolton 1972*a*; Hjellming and Wade 1971; Tananbaum *et al.* 1972*a*). The apparent identification of the companion in this system as a normal B0 Ib supergiant yields an estimate of 3–6 $M_\odot$ for the minimum mass of the X-ray source. This is considerably greater than the maximum mass of either a uniformly rotating white dwarf or a neutron star and has led to speculation that Cyg X-1 may be a black hole (Webster and Murdin 1972; Bolton 1972*a*; Ruffini 1972).

There is some difficulty in understanding how a black hole can be formed in a close binary system (see, e.g., Ostriker and Davidson 1973), and similar difficulties arise for neutron stars. In addition, none of the presently existing models of the compact X-ray sources can account for more than one type of source. The observed similarities among the compact X-ray sources (e.g., X-ray luminosities $\sim 10^{35}$–10^{38} ergs s^{-1}, membership in close binary systems, etc.) suggest, however, that a unified theory may be possible. We have accordingly sought a class of models which is sufficiently general so that any of the compact X-ray sources can be understood as a variant of the basic model and which at the same time fits naturally into the theory of stellar evolution in close binary systems. In this paper we argue that a basic model in which one component of a close binary is a differentially rotating, degenerate dwarf (DRDD) provides just such a class.[1]

[1] A similar model has recently been proposed independently by Brecher and Morrison (1973).

In § II we discuss some general features of evolution in close binary systems and sketch an evolutionary scheme that leads naturally to the occurrence of differentially rotating degenerate dwarfs in these systems. The properties of these objects are then outlined in § III. Possible sources of the X-ray luminosity are considered in § IV, and in § V we show that energy losses can lead to spinup of any model of this class on roughly the observed time scale. In § VI we conclude by discussing possible difficulties of our hypothesis, and by suggesting some observational tests.

II. EVOLUTION

It is known or inferred that the compact X-ray sources occur in close binaries (Gursky 1972); however, the fact that none of the previously known close binary systems are also X-ray sources[2] implies that X-ray emission requires special conditions. The short, transient periodicities of Cyg X-1 and the periods of the pulsed X-ray sources Cen X-3 and Her X-1 imply that the X-ray sources have radii $\leqslant 10^9$ cm. The fact that Cyg X-1, Cen X-3, Her X-1, and SMC X-1 (Webster *et al.* 1972) all seem to be the less massive members of their respective systems strongly suggests that in each case the compact star was originally the more massive of the two and that the system has evolved with considerable mass exchange. The observational evidence for extensive mass transfer currently taking place in several sources (Schreier *et al.* 1972) and theoretical calculations of stellar evolution in close binaries both support this view.

From an evolutionary standpoint, the presence of either a neutron star or a black hole in a close binary system is somewhat difficult to understand. It seems likely that the formation of a black hole must occur on a dynamic time scale, as is the case for neutron stars (Colgate and White 1966). Not only is the enormous gravitational energy released in such a collapse, $\sim 10^{53}$ ergs, of sufficient magnitude to disrupt the remainder of the star (of which the neutron star or black hole constitutes the collapsed core), but also it is released in a time much shorter than the hydrostatic readjustment time of the outer layers. Even if the ensuing violent (supernova) explosion is incapable of disrupting the binary system (Colgate 1970; McCluskey and Kondo 1971), it seems inconceivable that the spectrum of the companion star would show no evidence of this event. The spectra of the massive companions seem to be completely normal, however (Webster and Murdin 1972; Bolton 1972*b*; Crampton and Hutchings 1972). In addition, if neutron stars were the explanation of, e.g., the pulsed X-ray sources, one would expect to find ordinary radio pulsars in some close binary systems (since there can be an extended interval, perhaps $\sim 10^7$ years, during which the companion does not transfer mass onto the neutron star and thus block the radio pulses). However, *none* of the ~ 80 known pulsars are members of binary systems.

In contrast, stellar evolution may lead naturally to the formation of DRDDs in close binary systems. For the sake of definiteness, we consider a system with stars initially of 9 $M_\odot$ and 3.1 $M_\odot$ at a separation of 30 $R_\odot$ (Kippenhahn and Weigert 1967). If the 9 $M_\odot$ star in its main-sequence phase has angular momentum J_* appropriate either to normal rotation (Allen 1964) or to synchronous rotation, then $J_* \sim 10^{52}$–10^{53} g cm^2 s^{-1}. After $\sim 2 \times 10^7$ years, hydrogen exhaustion occurs in the 9 $M_\odot$ star, and the helium core contracts while the hydrogen-rich envelope expands to fill the Roche lobe. This star now rapidly sheds its mass, which flows through the inner Lagrangian point onto the companion (Kippenhahn and Weigert 1967; Paczyński 1971). After $\sim 4 \times 10^4$ years, when mass exchange terminates, the system consists of a remnant 2 $M_\odot$ nearly pure He star of radius ~ 0.3 $R_\odot$ in orbit at 56 $R_\odot$ around a normal 10 $M_\odot$ main-sequence star. The entire subsequent evolution of the compact He star

[2] We have searched Batten's (1967) catalog of approximately 700 close binaries for coincidences with the *Uhuru* X-ray sources (Giacconi *et al.* 1972) and have found *no* coincidences within the *Uhuru* error boxes.

will then be completed in $\sim 5 \times 10^6$ years (Divine 1965); i.e., less than the main-sequence lifetime $\sim 2 \times 10^7$ years of the 10 $M_\odot$ companion.

It appears unlikely that much angular momentum can be transferred from the 2 $M_\odot$ He core to the envelope which is lost during this first phase of mass exchange. Thus the angular momentum of the remnant core is $J \sim 10^{-2} J_* \sim 10^{51}$ g cm^2 s^{-1}. The ratio of rotational kinetic to gravitational energies at this stage is $T/|W| \sim J^2/GM^3R \sim 10^{-2}$, and rotation thus cannot yet significantly affect the evolution. The mass of the remnant He star is too great to be supported by the pressure of degenerate electrons, and it therefore contracts as various nuclear fuels are exhausted until, near a radius $R \sim 10J^2/GM^3 \sim 2 \times 10^9$ cm, where $T/|W| \sim 0.1$, rotation begins to slow the evolution. Because of the complex, multiple shell-burning structure of the star, a quantitative discussion of these phases is not yet possible. However, the qualitative nature of the subsequent contraction can be seen as follows:

At any point within the star we may define a local, Keplerian, rotation frequency, Ω_K:

$$\Omega_K{}^2 \equiv \frac{GM_r}{r^3} = \frac{4\pi}{3} G\bar{\rho}(r) , \tag{1}$$

where $\bar{\rho}(r)$ is the mean density of mass M_r interior to r; the orbital kinetic energy of a mass element rotating at this frequency just balances gravity. Thus since $\bar{\rho}(r)$ is a decreasing function of r, the difference between Ω_K and the true rotation rate of a *uniformly* rotating object is least at the equator. Consequently, if the 2 $M_\odot$ remnant has somehow managed to remain in uniform rotation at this stage,[3] the equatorial region first achieves an angular rotation frequency comparable to Ω_K, and further contraction of this mass shell is halted. Cylindrical mass shells closer to the rotation axis continue to contract, however, until the orbital kinetic energy of each shell successively becomes great enough to support the weight of the overlying layers, and the star is ultimately left in a flattened, differentially rotating configuration perhaps resembling the models constructed by Ostriker and Bodenheimer (1968).

III. PROPERTIES OF DRDD

Ostriker and Bodenheimer have shown that *equilibrium* models of differentially rotating degenerate dwarfs can be constructed for arbitrarily large values of stellar mass and total angular momentum. The ranges of mass and rotation period for which *stable* equilibrium models are possible are of course restricted by the occurrence of various instabilities, as Ostriker and Bodenheimer have noted (however, much greater ranges are possible than in the case of uniformly rotating objects). Dynamical instability due to fission occurs for objects with large angular momentum and small mass. Conversely, objects with small angular momentum and large mass (and hence large central densities) are expected to be dynamically unstable due to inverse β-decay (although this has not been explicitly shown for differentially rotating models; see especially Gribbin 1969) and to general-relativistic effects. A further limitation is imposed by secular instabilities, analogous to those which determine the point of bifurcation of the Jacobi ellipsoids from the Maclaurin spheroids, that may set in for configurations with $T/|W| \gtrsim 0.14$ (Ostriker and Tassoul 1969).

Most of the equilibrium models constructed by Ostriker and Bodenheimer lie within the limitations imposed by these constraints and are thus stable, except for viscous effects; these models have masses in the range $0 < M \lesssim 3\ M_\odot$ and equatorial

[3] The assumption of uniform rotation at this stage is probably overly conservative; the strongly nonhomologous contraction during these phases is likely to lead to markedly nonuniform rotation even earlier in the evolution (Van Horn 1972).

rotation periods 4 s $\leqslant P \leqslant$ 20 s (the polar regions typically rotate faster by factors $\sim$2–3). These limits, however, are dependent upon the distribution of angular momentum with mass, and other choices of the angular-momentum distribution (Gribbin 1969) may considerably extend the ranges of both mass and period for which stable models can exist. Since the equatorial rotation period varies as

$$P \sim J^3/G^2M^5 \tag{2}$$

for objects in which the centrifugal force due to extensive differential rotation is comparable to gravity, the shortest periods occur for configurations having low angular momentum and high mass. Thus the shortest period of a uniformly rotating, degenerate dwarf (URDD) is also in some sense the minimum period possible for a DRDD of the same mass. For example, the shortest rotation period of a 1.4 $M_\odot$ URDD is 2.2 s (Monaghan 1966); for objects with masses closer to or beyond the limit for URDDs, $M_{\rm lim} \approx 1.49\ M_\odot$ (Roxburgh 1965), much shorter periods are possible (Gribbin 1969; Hartle and Thorne 1968); less massive DRDDs must have longer periods.

Firm estimates of the minimum periods of our basic model thus exist and are short enough to accommodate the 1.24-s period of Her X-1. If the low masses suggested for Cen X-3 (Wilson 1972) and for Her X-1 (Crampton and Hutchings 1972) are confirmed, however, our model would become untenable for these sources.[4] The discovery of a pulsating X-ray source with a period $\ll$1 s would also pose extreme difficulties for our theory; however, such sources have yet to be discovered.

We have made use of the observed properties of all of the compact X-ray sources in trying to find a *class* of models that is sufficiently general to permit the observed variety of these sources. However, there is at present no *single* source which simultaneously requires both large mass (and thus strong differential rotation) and short period (and thus nearly uniform rotation). In fact, the physical limitations of our model show a remarkable correlation with the systematics of the observed X-ray sources: Where there is a large mass (as in Cyg X-1), thus, in our model, requiring strong differential rotation to support the star, no regular X-ray pulsations are found. Conversely, it is in sources that have short periods (as in Her X-1), thus requiring almost uniform rotation, that regular X-ray pulsations are seen.

IV. X-RAY EMISSION

It seems possible to understand the pulsed X-ray emission from Cen X-3 and Her X-1 only by assuming the existence of strong surface magnetic fields in these objects. This immediately suggests a close analogy with pulsars (see below), but the existence of strong fields in differentially rotating objects poses certain conceptual difficulties. We consider these problems next, bearing in mind the distinction just made between objects in strong differential rotation and those in which the rotation is nearly uniform.

Models of DRDDs have recently been constructed in which a fluid (Durisen 1972) or partially solid (Africk 1971) cylindrical core is in uniform rotation. The lifetimes of these configurations are very long: of the order of the viscous dissipation time for the fluid core and of the crystallization (evolutionary) time scale for the solid. For objects in which the rotation is uniform over most of the star (i.e., for our model of the pulsed X-ray sources), the differential rotation is limited to an outer, cylindrical region near the equator. In such a model a strong oblique magnetic field threading only the uniformly rotating core may be possible. (Any component of the field initially threading both the core and the differentially rotating envelope would very rapidly be dragged out into a predominantly toroidal configuration in the envelope, thus becoming

[4] Ostriker and Davidson (1973) and van den Heuvel and Heise (1972) have given arguments against the restriction to low mass for these sources.

effectively decoupled from the differential motions.) If such field configurations can be achieved, these models could provide a plausible basis for understanding the pulsed sources.

Degenerate dwarfs more massive than $M_{\rm lim}$ must have extensive differential rotation. In such objects, a permanent magnetic field would become strongly tangled and twisted by the differential motion, and *persistent* pulsed emission could not occur. *Transient* periodicities might still exist, however. It is interesting to note in this regard that Cyg X-1, which has $M \gg M_{\rm lim}$, has been found to exhibit strong transient periodicities in the range 10^{-3} to 10 s (Schreier *et al.* 1971).

If these arguments are correct, a pulsar-like emission mechanism may be possible within this class of models. Because magnetic flux is conserved in the formation of degenerate dwarfs as well as neutron stars, the magnetic field of either a pulsar or a magnetic A star can be scaled to the dimensions of a degenerate dwarf, and yields $B \sim 10^8$ gauss. A naïve application of the well-known expression for the rate of energy loss of a rotating magnetic dipole then gives

$$L \sim \tfrac{2}{3}B^2R^6\Omega^4/c^3 \sim 10^{37}\ \text{ergs s}^{-1}\,, \tag{3}$$

where we have used the equatorial radius $R = 4.7 \times 10^8$ cm and equatorial rotation period $P = 4.5$ s of Ostriker and Bodenheimer's 2.26 $M_\odot$ model 10. This value is in good agreement with the observed X-ray luminosities of the compact X-ray sources (Gursky 1972). Although it is quite unlikely that the true emission mechanism for these sources is actually so simple, this agreement is quite encouraging.

Since many (if not all) of the compact X-ray sources occur in close binaries in which extensive mass transfer is taking place, an additional source of the X-ray luminosity may be provided by accretion (Prendergast and Burbidge 1968; Lamb, Pethick, and Pines 1972; Pringle and Rees 1972). For a degenerate dwarf, the gravitational potential energy gained by infalling matter is more than sufficient to produce X-rays, and for a luminosity $L \sim 10^{37}$ ergs s^{-1}, the required rate of mass transfer is

$$\dot{M} \sim L/(GM/R) \sim 2 \times 10^{-7}\ M_\odot\ \text{year}^{-1}\,, \tag{4}$$

where we have again used the parameters of Ostriker and Bodenheimer's model 10. This is not excessive in comparison with either the observational data or the theoretical results of Kippenhahn and Wiegert (1967): $\sim 7\ M_\odot$ in $\sim 4 \times 10^4$ years.

It is rather remarkable that in models of this class the rate of energy loss is relatively insensitive to the characteristic rotation frequency. Because rotation plays an important role in the support of these stars, $\Omega^2 \sim \alpha GM/R^3$, where $\alpha \sim 0.1$. Equation (3) then gives $L \sim \alpha^2G^2B^2M^2/c^3$. Thus for either magnetic dipole emission or accretion, sources with periods as long as 10–20 seconds are possible according to this model. For example, Ostriker and Bodenheimer's 2.26 $M_\odot$ model 4, with $J = 5.77 \times 10^{50}$ g cm^2 s^{-1}, has an equatorial rotation period $P = 18.2$ s; yet according to equation (3) it also yields $L \sim 10^{37}$ ergs s^{-1}. (It is interesting to note that Kestenbaum *et al.* 1971 have reported a transient periodicity of just this order in the compact X-ray source Sco X-1.)

V. SPINUP

Perhaps the most intriguing characteristic of this class of models is that, in contrast to neutron stars, both rotational energy loss and accretion can cause the source to *spin up*. This is a direct consequence of the fact that rotation plays an essential role in the support of these objects.

The total energy E of a DRDD is, by virtue of the virial theorem,

$$E = \tfrac{1}{2}W \tag{5}$$

where $W \sim -GM^2/R$ is the gravitational potential energy, and R is the equatorial radius of the star. Loss of energy from such an object thus requires that it become more tightly bound, and conservation of the angular momentum $J \sim M\Omega R^2$, where Ω is the equatorial rotation frequency, then dictates that the star must spin up. The rate of spinup is given by

$$\frac{1}{\tau} \equiv \frac{\dot{\Omega}}{\Omega} \approx \frac{4\dot{E}}{W} - \frac{5\dot{M}}{M} + \frac{\dot{J}}{J}, \tag{6}$$

where the terms involving $\dot{M}$ and $\dot{J}$ take account of accretion from the companion star. If we neglect these terms, for the case of pulsar-like emission, equation (6) gives

$$\tau \sim +4 \times 10^6 \text{ years}, \tag{7}$$

for a typical X-ray luminosity $-\dot{E} \sim 10^{37}$ ergs s^{-1} and $W = -4.8 \times 10^{51}$ ergs (appropriate to Ostriker and Bodenheimer's 2.26 $M_\odot$ model 10). If accretion is the source of luminosity, and the star is in strong differential rotation, then $4\dot{E}/W \approx 10\dot{M}/M - 4\dot{J}/J$, and equation (6) becomes

$$\frac{1}{\tau} \approx 5\frac{\dot{M}}{M} - 3\frac{\dot{J}}{J} \tag{8}$$

(cf. also eq. [2]). Numerical differentiation of the Ostriker and Bodenheimer models yields the comparable result $1/\tau \approx 4\dot{M}/M - 2\dot{J}/J$. If we take $\dot{J}/J \sim +\dot{M}/M$, as suggested by consideration of the process of mass transfer onto a DRDD in a close binary, the accretion rate given by equation (4) yields (again for Ostriker and Bodenheimer's model 10)

$$\tau \sim +6 \times 10^6 \text{ years}. \tag{9}$$

Both of these estimates are longer than the observations indicate ($\sim 5 \times 10^4$ years for Cen X-3 and $\sim 10^5$ years for Her X-1: Tananbaum 1972). However, higher luminosities, greater accretion rates, or smaller binding energies all produce spinup on shorter time scales.

VI. SUMMARY, POSSIBLE DIFFICULTIES, AND SUGGESTED OBSERVATIONAL TESTS

We have shown that a differentially rotating, degenerate dwarf in a close binary system provides a possible model for the compact X-ray sources. We have argued that such objects may be a natural result of stellar evolution in close binaries, although quantitative calculations are needed to confirm this. Because DRDDs can have masses $\gtrsim 3\ M_\odot$, as needed for Cyg X-1, black holes are *not* essential to an understanding of this system. In such massive objects, magnetic fields will be tangled by the strong differential rotation, and any periodic component of the emission will be transitory.

This type of model is also sufficiently flexible, however, so that periods as short as ~ 1 s can be achieved (by objects in nearly uniform rotation). In these models an oblique magnetic dipole of $\sim 10^8$ gauss threading only the uniformly rotating core seems a possible mechanism for producing pulsed emission. A mean rate $\sim 10^{37}$ ergs s^{-1}, as required for X-ray sources such as Her X-1 appears quite reasonable.

In either case, energy losses cause the model to spin up on a time scale $\sim 10^6$ years. There are a number of possible difficulties with this model, however. Most serious is the necessity of postulating strong magnetic fields in stars with extensive differential rotation; models of such objects have not yet been constructed. In addition, details of the mechanism of X-ray emission are obscure, although either a pulsar-like emission mechanism or accretion are possibilities. Despite these theoretical difficulties, the merits of this hypothesis seem to us sufficient to warrant subjecting it to observational test. We therefore conclude by suggesting a few tests that appear to be crucial for the validity of this theory.

Our hypothesis is most sensitive to the relation between mass and period of the pulsating sources. In particular, a mass $M \sim 1.2$–$1.5\ M_{\odot}$ is essential for our model of Her X-1. The identification of this source with the optical variable HZ Her may allow an accurate mass to be obtained for this object. This would permit a direct check of the theory and is probably the single most crucial test likely to be presently possible. Verification of a mass much less than $1.2\ M_{\odot}$ for either Her X-1 or Cen X-3 would make our model untenable for these sources. Similarly, the discovery of a pulsating source with period $\ll 1$ s could not be understood within the framework of this model, while the discovery of long (~ 10–20 s) periodicities in the X-ray sources would provide strong confirmation for these ideas.

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