B. Datta

Disk Luminosity for Accreting, Weak Magnetic Field Neutron Stars in the "Slow" Rotation Approximation

Abstract

For accretion onto neutron stars possessing weak surface magnetic fields and substantial rotation rates (corresponding to the secular instability limit), we calculate the disk and surface layer luminosities general relativistically using the Hartle & Thorne formalism, and illustrate these quantities for a set of representative neutron star equations of state.

I Introduction

Disk accretion onto a neutron star possessing a weak surface magnetic field provides interesting X-ray emission scenarios, and is relevant for understanding X-ray bursters and low-mass X-ray binaries (e.g., van Paradijs 1991). An important aspect of this scenario is that the neutron star will get spun up to very short rotation periods ($\lesssim$ millisecond) over a time of the order of hundreds of millions of years. For such rapid rates of rotation, the relativistic effect of dragging of inertial frames in the vicinity of the neutron star is expected to be important. This will alter the trajectories of infalling particles as compared to the non-rotational case. We address this question and calculate the disk and surface layer luminosities incorporating the rotational effects in a general relativistic framework. We take the spun up neutron star to be rotating at a particular value, namely, the secular instability limit so as to illustrate the maximal reasonable effects of rotation. This corresponds to the late stages of accretion. We use the Hartle & Thorne (1968; hereafter HT) formalism, to describe the rotational space-time. This is valid for strong gravitational fields but in the limit of uniform rotation with a rate that is "slow" compared to the critical speed for centrifugal break-up. Neutron star models rotating at the secular instability limit (assuming the star to be homogeneous), relevant in the context of accretion induced spun up neutron stars, are within this limit (Datta & Ray 1983).

II Disk and boundary layer luminosities

Let x and x^* denote $r/2M'$ and $R'/2M'$ respectively (we take c = G = 1), where M' and R' are the mass and radius of the rotating star. Further let $x_{\rm orb}$ denote the radius of the innermost stable orbit corresponding to the rotating space time (in dimensionless units). The following two cases are possible:

Case (a): Radius of the star is greater than the innermost stable orbit radius

If an accretion disk were to form around a relatively large neutron star (i.e., $x^* > x_{\rm orb}$), the ingress of a particle of rest mass m_B from infinity to the inner disk boundary will release an amount of energy given by

$$E'_D = m_B\{1 - \tilde{E}_k(x^*)\} , \tag{1}$$

where $\tilde{E}_k(x^*)$ stands for the specific energy of the particle in the stable orbit just above the surface. The energy loss in the boundary layer will be

$$E'_S = m_B\{\tilde{E}_k(x^*) - \tilde{E}_o(x^*)\} , \tag{2}$$

where $\tilde{E}_o(x^*)$ is the energy of the particle at rest on the surface of the neutron star.

Case (b): Radius of the star is smaller than innermost stable orbit radius

In this case, $x^* < x_{\rm orb}$ and the accretion disk will extend inward to a radius corresponding to $x = x_{\rm orb}$. Now the energy released in the disk as the particle comes in from infinity to the innermost stable orbit will be

$$E'_D = m_B\{1 - \tilde{E}_{\rm orb}\} , \tag{3}$$

and the energy released in the boundary layer will be

$$E'_S = m_B\{\tilde{E}_{\rm orb} - \tilde{E}_o(x^*)\} . \tag{4}$$

Here, $\tilde{E}_{\rm orb}$ is the specific energy of the infalling particle in the innermost stable orbit. The quantities $\tilde{E}_k$ and $\tilde{E}_o$ and $\tilde{E}_{\rm orb}$, as a function of x, can be evaluated by numerically solving the condition for the turning point of the motion, the extremum of the energy and the minimum of the energy, corresponding to the Hartle-Thorne rotational space-time (see Datta, Thampan & Wiita 1995 for the details).

III Results and discussions

Our calculations are performed for the following equations of state of high density matter in neutron star interior: (A) Pandharipande (1971), (B) Wiringa UV14 + UVII model (Wiringa, Fiks & Fabrocini 1988), (C) Sahu, Basu & Datta (1993). Of these, models (A) and (C) are respectively very soft and very stiff equations of state and model (B) is intermediate in stiffness.

We consider neutron stars rotating with $\Omega = \Omega_s$, the secular rotational instability limit, given by

$$\frac{\Omega_s^2}{2\pi G\overline{\rho}} = 0.18 , \tag{5}$$

($\overline{\rho}$ is the average density of the star), so as to illustrate the maximal reasonable effects of rotation. The rotating neutron star's mass (M') and radius (R') are calculated by numerically evaluating the rotational deformations corresponding to the HT metric (Datta & Ray 1983; Datta 1988).

Table 1 summarizes the results. In the second and third columns of this table, we give values of the non-rotating mass M and the rotationally enhanced mass M' for a maximal reasonable rotation rate ($\Omega = \Omega_s$). Columns (4) and (7) show the disk and boundary layer luminosities for non-rotating configurations (E_D and E_S respectively). The values of E'_D and E'_S, including rotational effects treated consistently within the HT framework, are given in columns (5) and (8). All values of luminosity listed in the table are in units of the baryonic rest mass. The boundary layer luminosity values listed in Table 2 do not include corrections for the energy that goes into spinning up the neutron star. We have made estimate of this correction following the prescription of Popham & Narayan (1995) for the case of 1.4 $M_\odot$ neutron star corresponding to the EOS model by Wiringa et al. 1988), and find this correction to be unimportant for $\Omega = \Omega_s$ (Datta, Thampan & Wiita 1995).

In our notation, the total luminosity is: $L = (E'_D + E'_S)\dot{M}c^2$, with $\dot{M}$ the mass accretion rate. According to our calculations, typical values for $(E'_D + E'_S)$ are of the order of 0.2. A typical value of L equal to 10^{37} ergs s^{-1} would then correspond to $\dot{M} \sim 5.6 \times 10^{16}$ g s^{-1}. Such accretion rates are close to the ones estimated in X-ray binaries (Ghosh & Lamb 1991), so that our computations are relevant for systems with significant accretion onto old neutron stars whose surface magnetic fields have undergone substantial decay (to about 10^8 G). Under these circumstances of weak neutron star magnetic fields, we have shown that an incorporation of general relativistic rotational effects always increases the disk luminosity, and usually decreases the boundary layer luminosity. For accretion spun-up neutron star, these effects can be substantial to merit their consideration in analyses of observations of low-mass X-ray

Table 1: Disk and Boundary Layer Luminosities

EOS (1)	$M/\mathrm{M}_\odot$ (2)	$M'/\mathrm{M}_\odot$ (3)	E_D (m_0c^2) (4)	E'_D (m_0c^2) (5)	$\Delta E_\mathrm{D}/E_\mathrm{D}$ (6)	E_S (m_0c^2) (7)	E'_S (m_0c^2) (8)	$\Delta E_\mathrm{S}/E_\mathrm{S}$ (9)
A	1.045	1.121	0.057	0.071	0.2379	0.138	0.130	−0.0534
	1.289	1.371	0.057	0.074	0.2926	0.215	0.206	−0.0431
	1.319	1.400	0.057	0.074	0.2957	0.228	0.218	−0.0423
	1.400	1.476	0.057	0.075	0.3099	0.276	0.266	−0.0395
	1.414	1.485	0.057	0.075	0.3176	0.298	0.285	−0.0409
B	1.053	1.153	0.055	0.063	0.1541	0.097	0.096	−0.0114
	1.282	1.400	0.057	0.071	0.2430	0.131	0.126	−0.0384
	1.400	1.526	0.057	0.074	0.2896	0.150	0.144	−0.0439
	1.680	1.817	0.057	0.075	0.3148	0.201	0.194	−0.0359
	2.188	2.305	0.057	0.078	0.3653	0.355	0.342	−0.0369
C	1.017	1.128	0.045	0.051	0.1140	0.066	0.067	0.0189
	1.261	1.400	0.052	0.059	0.1455	0.085	0.085	0.0075
	1.400	1.553	0.055	0.064	0.1686	0.097	0.097	−0.0010
	1.644	1.817	0.057	0.070	0.2260	0.120	0.118	−0.0224
	2.592	2.771	0.057	0.076	0.3274	0.263	0.255	−0.0324

binaries. An extension of this study for rapidly rotating neutron stars, going beyond the HT approximation, has been done (Datta & Thampan 1997), which will be reported in a future publication.

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References

Datta, B. & Ray, A. 1983, MNRAS, 204, 75
Datta, B., 1988, Fund. Cosmic Phys., 12, 151
Datta, B., Thampan, A.V. & Wiita, P.J. 1995, J. Astrophys. Astr., 16, 357
Datta, B. & Thampan, A.V. 1997, preprint
Ghosh, P. & Lamb, F.K. 1991, in Neutron Stars: Theory and Observations, ed. J.

Ventura & D. Pines (Dordrecht: Kluwer), 363
Hartle, J.B. & Thorne, K.S. 1968, ApJ, 153, 807 (HT)
Pandharipande, V.R. 1971, Nucl. Phys., A178, 123
Popham, R. & Narayan, R. 1995, ApJ, 442, 337
Sahu, P.K., Basu, R. & Datta, B. 1993, ApJ, 416, 267
van Paradijs, J. 1991, in Neutron Stars: Theory and Observations, ed. J. Ventura & D. Pines (Dordrecht: Kluwer), 245
Wiringa, R.B., Fiks, V. & Fabrocini, A. 1988, Phys. Rev. C, 38, 1010

Authors' Address

Indian Institute of Astrophysics, Bangalore 560 034, India

Raman Research Institute, Bangalore 560 080, India