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The Lower Temperature Limit of Accretors

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Abstract—There should be a universal correlation between the main observational parameters of magnetized accreting stars (neutron stars, white dwarfs, and possibly T Tauri stars): their luminosities, periods, and temperatures. To first approximation, such a dependence is obeyed reasonably well for X-ray pulsars, intermediate polars, and T Tauri stars. In contrast, the parameters of anomalous pulsars (so-called "magnetars") and soft gamma-ray repeaters differ sharply from this dependence, and even occupy a "forbidden" region in the parameter space. This presents a serious argument against the idea that these are accreting neutron stars.

1. INTRODUCTION

The theory of accretion onto magnetized stars was developed in connection with the discovery and subsequent study of X-ray pulsars in binary systems [1]. Although we are still far from being able to construct a complete theory, to first approximation, the main elements of the theory discussed as early as the 1970s can still be considered to be on firm ground. The most important of these include the following.

(1) The size of the magnetosphere of the accreting star is close to the so-called Alfven radius:

$$R_A = \left(\frac{\mu^2}{2\dot{M}\sqrt{2GM_x}}\right)^{2/7},$$

(2) During its evolution under the action of the accelerating and decelerating torques in the system, the accreting star tends to approach an equilibrium state in which the size of the magnetosphere is close to the corotation radius ($\kappa \simeq 1$) [2]:

$$R_A = \kappa R_c = \kappa (GM_x/\omega^2)^{1/3} \quad ,$$

(3) The time over which this equilibrium is attained is always less than the characteristic lifetime of the star in the accretion stage:

$$t_{eq} = \frac{I\omega}{\dot{M}\sqrt{GMR_c}} = \frac{M_x}{\dot{M}}\left(\frac{R_x}{R_c}\right)^3 \ll \frac{M_x}{\dot{M}}.$$

Generally, speaking, these last two points suppose that a disk-accretion regime is realized; this is obviously applicable for systems in which there is a flow of material through the inner Lagrange point, but is also a quite likely scenario for accretion of material from a stellar wind. Here, we are not considering only systems in which there is disk accretion. Recall that the main observational quantities associated with X-ray pulsars are their luminosity L, period P, period derivative ($\dot{P}$), and characteristic spectral temperature (kT_{spec}). The first three quantities are obviously interconnected, since the luminosity is determined by the accretion rate, which also determines the rate of change of the period. Here, we concentrate on the fact that the three points listed above imply that the luminosity and period of any accreting star (accretor) should be correlated with the characteristic temperature of its radiation.

2. A NEW PICTURE FOR X-RAY PULSARS

Let us consider a lower limit for the characteristic temperature of the radiating region of an accretor. As a first approximation, we can use the Stefan–Boltzmann formula

$$L = S\sigma T^4. \quad (1)$$

We can estimate the size of the region onto which the accreting material falls based on the dipole structure of the magnetic field of the accretor [3]:

$$S = 2\pi R_x^2 \epsilon^2, \quad (2)$$

where ϵ is the opening angle of the polar column, which is determined by the accretor's radius R_x and the size of the Alfven zone R_A via the expression

$$\epsilon = \left(\frac{R_x}{R_A}\right)^{1/2}. \quad (3)$$

Let us now also take into consider the fact that, during its evolution, the accretor tends toward a state

Table 1. Temperatures of accretors

Type	Name	$kT_{\min}$, eV	kT_{spec}, eV	kT_{eff}, eV	$f(L)$
Neutron stars	Her X-1	3754	19000	13593	1.398
	4U 0115+63	4965	8000	5631	1.421
	X0331+53	4633	15500	11089	1.398
	Cen X-3	7045	14300	8511	1.680
	Vela X-1	6954	17500	13112	1.335
Magnetars	AXJ 1845–0258	1752	640	541	1.182
	1E 2259+586	1259	410	365	1.121
	1E 1841–045	1911	550	465	1.182
	4U 0142+615	2456	390	314	1.240
	1E 1048–5937	1964	640	530	1.206
	1RXS J17084.9	1986	460	386	1.190
Soft gamma-ray repeaters	SGR 1900+14	696	500	486	1.027
	SGR 1806–20*	76000	9000	5357	1.680
	SGR 1627–41	1107	1300	1181	1.10
Burster	SAXJ 1808.4–36	81	200	223	0.896
Polar	AM Her	3.868	28	16	1.68
Intermediate polars	DQ Her	0.937	20	11.9	1.68
	SW UMa	3.307	70	41.6	1.68
T Tauri star	T Tau	0.290	0.43	0.25	1.68

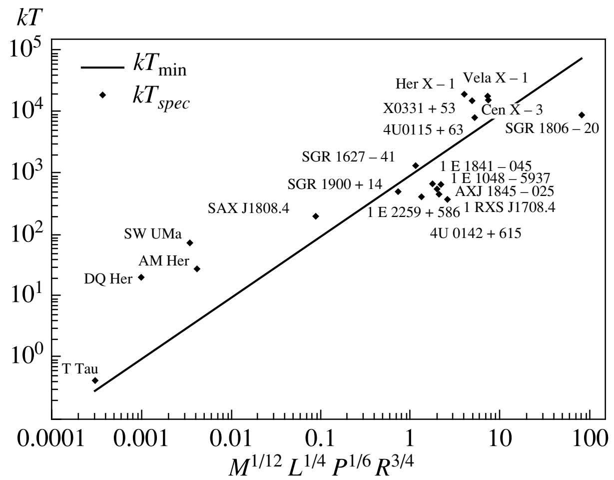
* The temperature of the X-ray flare of the source is indicated.

in which the Alfven radius approaches the corotation radius R_c, i.e.,

$$R_A = \kappa R_c, \qquad (4)$$

where κ is a dimensionless coefficient that is close to unity. Further, using the definition of the corotation radius and (1)–(4), we obtain the minimum temperature of the accretion zone in the blackbody approximation

$$kT_{\min} = 0.94 \frac{M_1^{1/12} L_{35}^{1/4} P^{1/6}}{R_6^{3/4}} \text{ kev}. \qquad (5)$$



Dependence of the spectral temperature on the parameters of the accretor. kT is measured in eV, M in $M_\odot$, L in 10^{35} erg/s, P in s, and R in 10^6 cm.

In (5), the mass is normalized to one solar mass, the luminosity to 10^{35} erg/s, the period to one second, and the radius to 10^6 cm. The corresponding relation is shown by the line in Fig. 1.

We emphasize again that (5) gives a lower limit for the temperature of the accretor's radiation zone. As a consequence of Rayleigh–Taylor instability, the accreting material channeled in the near-polar zones by the magnetic force lines falls not onto the polar cap of the accretor, but instead into a narrow ring of much smaller area [1]. It is obvious that the resulting lower limit for the temperature can be applied to any magnetized accretor independent of its nature—a neutron star, white dwarf, or ordinary star. The main thing is that we are dealing with magnetized objects accreting from a disk. There is no doubt that such objects are found among X-ray pulsars, X-ray bursters, cataclysmic variables (polars and intermediate polars), and possibly T Tauri stars [4].

Table 2. Used numerical values of main accretor characteristics

Type	Name	P, s	L, 10^{35} эerg/s	R, 10^6 cm	$M/M_\odot$
Neutron stars	Her X-1	1.24	200	1.0	1.4
	4U 0115+63	3.61	300	1.0	1.4
	X0331+53	4.38	200	1.0	1.4
	Cen X-3	4.84	1000	1.0	1.4
	Vela X-1	283	63	1.0	1.4
Magnetars	AXJ 1845−0258	6.97	3	1.0	1.4
	1E 2259+586	6.98	0.8	1.0	1.4
	1E 1841−045	11.76	3	1.0	1.4
	4U 0142+615	8.69	10	1.0	1.4
	1E 1048−5937	6.44	5	1.0	1.4
	1RXS J17084.9	10.99	3.6	1.0	1.4
Soft gamma-ray repeaters	SGR 1900+14	5.16	0.09	1.0	1.4
	SGR 1806−20*	7.47	10^7	1.0	1.4
	SGR 1627−41	6.41	0.5	1.0	1.4
Burster	SAXJ 1808.4−36	0.0025	0.003	1.0	1.4
Polar	AM Her	11139.2	0.0002	700	1.0
Intermediate polars	DQ Her	71.07	0.00002	700	1.0
	SW UMa	954	0.0005	700	1.0
T Tauri star	T Tau	432000	0.0044	140000	1.0

* The luminosity of the X-ray flare is indicated. The masses and radii of neutron stars are not intended to be extremely accurate, but to represent their most likely values.

3. THE ROLE OF COMPTONIZATION

In the case of accreting neutron stars, we will use the model atmosphere of [5] to specify the relationship between the spectral X-ray temperature of the accretor kT_{spec} (which we will take to be the temperature in the best-fit approximation to the observed spectrum of the form $I \propto \exp^{-h\nu/kT_{spec}}$) and the effective temperature of the radiating region.

We wish to elucidate the effect of comptonization on the spectrum. We write for the relationship between kT_{spec} and $kT_{\rm eff}$

$$T_{spec} = f(L)T_{\rm eff}, \qquad (6)$$

where the function $f(L)$ has the form

$$f(L) = \begin{cases} 1.51(L/L_{\rm edd})^{0.04} & L \ll L_{\rm edd} \\ 1.68 & L \simeq L_{\rm edd} \end{cases}$$

The results of correcting for the effect of comptonization are presented in Table 1. We can see that, as before, the temperatures of observed accretors

Table 3. References to observational data for the accretors

Type	Name	Reference
Neutron stars	Her X-1	[6, 7]
	4U 0115+63	[6, 7]
	X0331+53	[6, 7]
	Cen X-3	[6, 7]
	Vela X-1	[6, 7]
Magnetars	AXJ 1845−0258	[8, 9, 10]
	1E 2259+586	[8, 9, 10]
	1E 1841−045	[8, 9, 10]
	4U 0142+615	[8, 9, 10]
	1E 1048−5937	[8, 9, 10]
	1RXS J17084.9	[8, 10, 11, 12]
Soft gamma-ray repeaters	SGR 1900+14	[13, 14, 15, 16]
	SGR 1806−20	[17, 18, 19, 20]
	SGR 1627−41	[21, 22, 23]
Burster	SAXJ 1808.4−36	[24, 25]
Polar	AM Her	[6, 26, 27]
Intermediate polars	DQ Her	[6, 28]
	SW UMa	[6, 29]
T Tauri star	T Tau	[4, 6]

are higher than their minimum values. The effect of comptonization is somewhat smaller in the case of other types of accretors—polars and T Tauri stars—but the discrepancy between the effective temperature and the minimum temperature remains large, even when the largest value of $f(L)$ is used for the correction (Table 1).

4. POLAR AND T TAURI SYSTEMS

The cataclysmic variable AM Her is a member of the subclass of polars. It is a binary system containing a magnetized white dwarf and a red dwarf. The red dwarf fills its Roche lobe. The orbital period and rotational period of the white dwarf are nearly coincident, $P_{spin} = 0.77P_{orb}$. It is thought that the magnetic field at the white-dwarf surface is $\sim 10^9$ G [6].

DQ Her is a cataclysmic variable classified as an intermediate polar. It is a binary system containing a white dwarf and a K−M star (the latter star's spectral type has not been established more precisely). The synchronization coefficient is $P_{spin} = 0.004P_{orb}$. The magnetic field at the white-dwarf surface is believed to be $\sim 10^6$ G [6].

SW UMa is another intermediate-polar cataclysmic variable, and periodically produces nova-like flares. It is a binary system containing a white dwarf and an $M2$ or later-type companion. The relationship between the orbital period of the system and the rotational period of the white dwarf is $P_{spin} = 0.195P_{orb}$ [6].

T Tauri stars are young stars whose accretion luminosities lie in the range from $0.02L_{\odot}$ to $0.2L_{\odot}$; we have adopted the luminosity $0.1L_{\odot}$) for our calculations for T Tau. The period of T Tau varies from 3 to 10 days, being on average 5 days. The mass of the white dwarf is $1 - 1.5M_{\odot}$, and the magnetic field at its surface reaches 10^4 G [4].

The numerical values for the characteristics of the accretors we have considered are listed in Table 2. References to this information are given in Table 3.

5. DISCUSSION

Let us consider the dependence for the lower limit of the accretor temperature (5) shown in the Figure, which plots the X-ray spectral temperature as a function of the generalized coordinate

$$\frac{M^{1/12}L^{1/4}P^{1/6}}{R^{3/4}}.$$

We chose the generalized coordinate so as to transform (5) into a linear relationship. Recall that the collection of accretor parameters in (5) is the result of combining expressions (1)–(4), so that the right-hand side of (5), and therefore the generalized coordinate plotted in the Figure, carries information about the accretor's rotational period, its luminosity, and, indirectly, its moment of inertia.

This same plot shows the temperatures kT_{spec} characterizing the observed spectra. Since the theoretical area of the accretion zone is clearly overestimated, and taking into account the effect of comptonization on the emerging radiation, we can be confident that points with kT_{spec} should lie above their theoretical values, or at the very least not be below them. The region below the theoretical line (5) is therefore a "forbidden zone" for sources whose luminosities are associated with accretion.

We can see from the Figure that the anomalous X-ray pulsars (magnetars) and soft gamma-ray repeaters lie in the "forbidden zone". Only SGR 1627–41 deviates slightly from this tendency. However, in contrast to the undoubted accretors, for which $kT_{spec} \gg kT_{\min}$, we have $kT_{\min} \simeq kT_{spec}$ for SGR 1627–41. We also emphasize that the position of SGR 1627–41 above the line corresponding to minimum accretor temperatures does not necessarily imply that the luminosity of this source cannot have a non-accretion nature.

The above discussion brings into doubt the accretional nature of the radiation of magnetars and soft gamma-ray repeaters. It is possible that another mechanism is responsible for their X-ray radiation. For example, one possible mechanism is the dissipation of magnetic fields $\sim 10^{14}$–10^{15} G [30, 31]. Thus, our proposed universal dependence based on the relationships between the characteristic temperature of the radiation zone of an accretor and its main properties—luminosity, period, mass, and radius—can add weighty arguments that the X-ray radiation of an individual object has an accretional (or nonaccretional) origin.

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