

Spectroscopic Constraints on the Surface Magnetic Field of the Accreting Neutron Star EXO 0748-676

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Gravitationally redshifted absorption lines of Fe XXVI, Fe XXV, and O VIII were inferred recently in the x-ray spectrum of the bursting neutron star EXO 0748-676. We place an upper limit on the stellar magnetic field based on the iron lines. The oxygen absorption feature shows a multiple component profile that is consistent with Zeeman splitting in a magnetic field of $\sim(1-2) \times 10^9$ G and for which the corresponding Zeeman components of the iron lines are expected to be blended together. In other systems, a field strength $\geq 5 \times 10^{10}$ G could induce a blueshift of the line centroids that would counteract gravitational redshift and complicate the derivation of constraints on the equation of state of the neutron star.

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An unusually long exposure by the XMM-Newton observatory of x-ray bursts from the accreting neutron star EXO 0748-676 revealed the existence of redshifted absorption lines such as the $n = 2 \rightarrow 3$ transitions of hydrogenlike and heliumlike iron and the $n = 1 \rightarrow 2$ ($Ly\alpha$) transition of hydrogenlike oxygen [1]. The common redshift of the lines, $z_{\text{obs}} = 0.35$, is consistent with absorption features from the surface of a neutron star with a composition of normal nuclear matter [2]. The observed equivalent width of the Fe lines, ~ 10 eV, is an order of magnitude larger than expected from thermal Doppler broadening at the inferred surface temperature of 1–2 keV, and so it may be dominated by the Stark effect [3]. Rapid rotation of the neutron star at a spin frequency of $\sim 10^2$ Hz may contribute substantially to the observed width of the redshifted lines [4]. Other identified lines do not show any significant redshift and are likely to be associated with gas far away from the neutron star surface.

Here we consider the potential contribution of the Zeeman effect to both the shift and the width of the observed lines. The detectability of this contribution

was first predicted in Ref. [5]. Indirect theoretical arguments suggest that the magnetic field of accreting neutron stars in low-mass x-ray binaries may have an amplitude of up to $\sim 10^{10}$ G [6,7]. Such a field could have important effects on the accretion flow near the star and on the existence of pulsations in its emission [8]. However, no direct measurement of the field strength has been reported so far.

A relatively weak magnetic field induces a Zeeman (or Paschen-Back [9]) splitting of an atomic level by an energy separation which is linear in the magnetic field strength, $\sim (eh/4\pi m_e c)(M_L + 2M_S)B = 5.8 \text{ eV}(M_L + 2M_S)(B/10^9 \text{ G})$, where M_L and M_S are the quantum numbers of the orbital angular momentum and the spin of the electron, respectively. The split transition lines associated with changes of $\Delta M_L = \pm 1$ and $\Delta M_S = 0$ would therefore be maximally separated by an energy,

$$(\Delta E)_{\text{split}} \sim 11.6 \text{ eV} \left(\frac{B}{10^9 \text{ G}} \right). \quad (1)$$

For a strong field, there is a net blueshift of the centroid of the transition line components, which is quadratic in B , and for hydrogenlike ions is given by [10–12]

$$(\Delta E)_{\text{shift}} \sim \frac{e^2 a_0^2}{8Z^2 m_e c^2} n^4 (1 + M_L^2) B^2 = 9.2 \times 10^{-4} \text{ eV} \left(\frac{Z}{26} \right)^{-2} n^4 (1 + M_L^2) \left(\frac{B}{10^9 \text{ G}} \right)^2, \quad (2)$$

where n and M_L are the principal and orbital quantum numbers of the upper state, a_0 is the Bohr radius, and Z is the nuclear charge ($= 26$ for Fe and 8 for O). The factor of Z^{-2} was added to account for the reduction in the square of the orbital radius of the last bound electron in heavy elements as compared to hydrogen.

Equation (1) implies that the intrinsic (redshift corrected) full width at half minimum of the Fe absorption lines in the neutron star EXO 0748-676 spectrum, $\delta E \sim 20$ eV, limits the strength of its surface magnetic field to a value $B \lesssim 1.7 \times 10^9$ G, assuming that a weak

splitting with $(\Delta E)_{\text{split}} < \delta E$ cannot be resolved but is rather blended by Stark broadening [3], rotational broadening [4], or the current instrumental sensitivity. This is the first direct limit on the magnetic field of a neutron star in a low-mass x-ray binary. An independent constraint on the field strength can be derived from the line shift. Because both the iron and oxygen features showed the same redshift, z_{obs} , for transitions with different Z and n , the Zeeman blueshift, $z_B \equiv -(\Delta E/E)_{\text{shift}}$, must be much smaller than the observed

redshift, $|z_B| \ll z_{\text{obs}}$. Equation (2) then implies $B \ll 5 \times 10^{10}$ G for the iron and oxygen lines, a much weaker upper limit than derived from the line width. More generally, $(1 + z_{\text{obs}}) = (1 + z_{\text{grav}})(1 + z_B)$, or equivalently $z_{\text{grav}} = (z_{\text{obs}} - z_B)/(1 + z_B)$, where z_{grav} is the gravitational redshift. An upper limit on the magnetic field strength from the line width translates to a lower limit on the gravitational redshift,

$$z_{\text{grav}} \geq \frac{z_{\text{obs}} + |z_{B,\text{max}}|}{1 - |z_{B,\text{max}}|}, \quad (3)$$

where a line with energy $E = hc/\lambda$ and an intrinsic (redshift corrected) wavelength width $\delta\lambda$ has an intrinsic energy width of $\delta E = hc\delta\lambda/\lambda^2$ and

$$|z_{B,\text{max}}| \equiv \left(\frac{E}{920 \text{ eV}}\right)^{-1} \left(\frac{Z}{26}\right)^{-2} \left(\frac{n}{10}\right)^4 \times (1 + M_L^2) \left(\frac{\delta E}{116 \text{ eV}}\right)^2. \quad (4)$$

For other neutron stars, constraints on the equation of state of the neutron star or the theory of gravity [2,13] could be complicated by the possible existence of a magnetic field with a strength $\geq 5 \times 10^{10}(n/3)^{-2}$ G. The magnetic effect can be isolated based on the particular dependence of the quadratic Zeeman shift on n and Z in Eq. (2). While the above analytical estimates are restricted to moderate fields [$\ll 10^{11}(Z/26)^2$ G], a precise evaluation of the same limits for arbitrary field strength in other systems can be done based on the tables in Ref. [14].

Although no multiple components are clearly seen for the iron lines, the Ly α absorption feature of hydrogenlike oxygen is split into multiple (possibly three) components in the observed spectrum [1]. If this splitting is caused by the Zeeman effect, it implies a magnetic field strength of $\sim 1.4 \times 10^9$ G (including the redshift correction) [15]. If the intrinsic width of the O VIII line is caused by rotational broadening (requiring a rotation period of ~ 10 ms), then for other lines $\delta\lambda \propto \lambda$, while Zeeman splitting results in a separation between the outer line components of $(\Delta\lambda)_{\text{split}} \propto \lambda^2$. Scaling in the late burst spectrum from the outer two O VIII absorption features centered at observed wavelengths of 25.2 and 26.4 Å, each with an observed width ~ 0.53 Å, down in wavelength to the Fe XXV absorption feature at 13.75 Å, implies a redshifted width $(1 + z_{\text{obs}})\delta\lambda \sim 0.29$ Å that is comparable to the extrapolated Zeeman split $(1 + z_{\text{obs}}) \times (\Delta\lambda)_{\text{split}} \sim 0.34$ Å for the iron line. Moreover, the Ly α line of oxygen should be split into a triplet while the Fe $^{24+} 2 \rightarrow 3$ line should have many more components (see Table A4.1 in [14]). Hence, we conclude that *the possible Zeeman components of the iron line may be blended together due to their finite width even though*

the splitting of the oxygen Ly α line is resolved. Zeeman splitting provides a viable alternative to the other interpretation of the multicomponent, broad profile of oxygen given by Cottam *et al.* [1], involving an extended outer atmosphere with a possible slow outflow and a self-reversed (W-shaped) absorption profile. The latter interpretation does not immediately explain why the W-shaped broad profile does not appear in the iron lines. The Zeeman interpretation predicts that all redshifted lines of observed wavelength $\lambda \geq 20$ Å would show a multicomponent profile with a wavelength split among its outer components that scales as λ^2 .

While the above evidence for a magnetic field is only tentative, future x-ray observations with longer exposure times (or further analysis and detailed modeling of existing data) can easily test the generic signatures of a Zeeman effect. The contributions of the Stark effect and the rotation of the neutron star to the width of the lines [3,4] can be separated by measuring the line width for transitions with different quantum numbers and line energies. A magnetic field strength of $\sim (1-2) \times 10^9$ G is rather plausible for accreting neutron stars in low-mass x-ray binaries, since these systems are believed to be the progenitors of millisecond radio pulsars which possess fields of 10^8-10^9 G [16]. Future x-ray observations with improved flux sensitivity and spectral resolution may provide conclusive evidence for the surface field strength in EXO 0748-676 and other accreting neutron stars.

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