A Note on the Discovery of Absorption Features in 1E 1207.4-5209 *

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Sanwal et al. [Astrophys. J. 574 (2002) L61] supposed that it is very difficult to interpret the absorption features in terms of cyclotron lines. However, we would like to address here that the possibility of the absorption being cyclotron resonance cannot be ruled out. We propose that the isolate neutron star, 1E 1207.4-5209 in the centre of supernova remnant PKS 1209-51/52, has a debris disc and is in a propeller phase, with an accretion rate $\sim 6 \times 10^{-11} M_\odot$*/year. In this scenario, 1E 1207.4-5209 could also be a bare strange star.*

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Strange (quark) star is composed of nearly equal number of up-, down-, and strange-quarks, and a few electrons for keeping neutralization of matter.[1,2] It has important implications for studying the phase diagram of strong interaction system whether this kind of quark stars exists. Recently, Xu[3] suggested that a featureless thermal spectrum could be a probe for identifying strange stars, since no bound charged particle is in discrete quantum states on the quark surface without strong magnetic field. Nonetheless, it is worth noting that discrete Landau levels appear for charged particles in strong fields.

Two absorption lines at ~ 0.7 and ~1.4 keV are detected from an isolate neutron star (1E 1207.4-5209) with *Chandra* by Sanwal *et al.*,[4] and are then confirmed with *XMM-Newton* by Mereghetti *et al.*[5] Certainly 1E 1207.4-5209 cannot be a bare strange star if those two lines are atomic-transition originated, although the stellar mass M and radius R may be derived by obtaining the gravitational redshift (as M/R) and the pressure broadening (as M/R^2) of the lines. However, if these double lines are caused by the Landau-level transition of electrons, 1E 1207.4-5209 could also be a bare strange star since no atom might be on the stellar surface. Sanwal *et al.*[4] addressed that the features are associated with atomic transition of once-ionized helium, and thought that it is hard to interpret the absorption features in term of cyclotron lines. However, we will find that the possibility of the absorption being cyclotron resonance cannot be ruled out. We will present, in this Letter, a short note to confute the interpretation of the recently discovered lines in the x-ray spectrum of 1E 1207-52, in which these spectral lines are testifying the presence of an atmosphere on the star which can absolutely not be a bare strange star.

Sanwal *et al.*[4] discussed two potential possibilities in generating the absorption features, i.e., cyclotron or atomic transition lines, but considered the former scenario unlikely. They hence suggested that the features are associated with atomic transitions of once-ionized helium. Here we hope to point out that all the criticisms about the cyclotron line mechanism by Sanwal *et al.* can be circumvented, so that such a possibility is not ruled out. In what follows, we answer their criticisms in turn.

1. The inferred field value, $B_{\rm e} = 3 \times 10^{12}$ G, based on P and $\dot{P}$, is significantly larger than the field $B_{\rm ce} \sim 10^{11}$ G derived by assuming that the 0.7 keV and 0.7 × 2 keV lines are the fundamental and the first harmonics, respectively.[4] However, it is possible that 1E 1207.4-5209 has a debris disc, which is currently conjectured for interpreting the enigmatic sources of anomalous x-ray pulsars and soft γ-ray repeaters in the literature (e.g., Ref. [6]), since it is in the centre of a supernova remnant. A recent discovery of a near-infrared counterpart to an anomalous x-ray pulsar (AXP)[7] (1E 1048) may be a hint of such a kind of a fallback accretion disc. The discovery of Israel *et al.*[8] strengthens the infrared association with the AXP 1E 1048.1-5937. In the case of this disc, 1E 1207.4-5209 provides a potential possibility for us to investigate the disc property by dividing the total braking rate into magnetodipole and disc ones, since the total rotational energy loss ($I\Omega\dot{\Omega}$ with I being the moment of inertia) is the sum of the dipole radiation power and the propeller energy loss $\dot{E}_{\rm d} = I\Omega\dot{\Omega}_{\rm d} \simeq -G\dot{M}M/R_{\rm m}$,[9] where M is the mass of centre star, $\dot{M}$ is the accretion rate, and the magnetosphere radius $R_{\rm m} \simeq 2.2 \times 10^{13} B_{12}^{4/7} \dot{M}^{-2/7}$ cm.

It is worth noting that most of the accretion material driven by viscosity in the fossil disc cannot fall onto the stellar surface because of centrifugal forces acting on the matter, but is ejected by the boundary reaction during the propeller phase. The magnetodipole spin down $\dot{\Omega}_{\rm m} \simeq -8 \times 10^{-16}\,{\rm s}^{-2}$ for a

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pulsar with polar field $B_{\rm ce}$, and then $\dot{\Omega}_{\rm d} = \dot{\Omega} - \dot{\Omega}_{\rm m} \simeq -7 \times 10^{-13}\,{\rm s}^{-2}$. The fossil disc torque dominates, which could be the reason that this source is radio quiet (otherwise, a source may be radio loud if the dipole radiation torque dominates).

Therefore, the accretion rate $\dot{M} \simeq 9.1 \times 10^{15}$ g/s$\sim 6.4 \times 10^{-11} M_\odot$ per year. We find $R_{\rm m} \simeq 1.6 \times 10^8$ cm, the radius of light cylinder $R_{\rm L} \simeq 2 \times 10^9$ cm, and the corotating radius $R_{\rm C} \simeq 9.5 \times 10^7$ cm. These radii are consistent with the propeller requirement: $R_{\rm C} \lesssim R_{\rm m} < R_{\rm L}$.

In addition, the age problem[5] that the characteristic age $\tau_{\rm c} = 200 - 900$ kyr is much larger than the estimated age ~ 7 kyr for the remnant PKS 1209-51/52 might also be solved in this scenario.

2. The 0.7 keV line is not much stronger than the 1.4-keV one.[4] It is true that the oscillator strength of the first harmonic is much smaller than that of the fundamental in the weak-field limit, but this does not mean that the absorption-like dips would have significant differences. In fact, the spectrum profile should be calculated by modelling the resonant cyclotron radiation transfer. For instance, even for a field of $B = 1.7 \times 10^{12}$ G (in this case, the ratio of the oscillator strength could be ~ 0.04), those two spectrum lines calculated could be similar in depth,[10] depending on radiative geometry. Observationally, the cyclotron absorption depth of the fundamental is *not* much stronger than that of the first harmonic (e.g., the discovery by Trümper *et al.*[11] with $B \sim 3 \times 10^{12}$ G). In addition, the observation does show that the integrated photons absorbed by the fundamental transition are much more than those by the first harmonic transition.

3. The charge density in the star magnetosphere cannot be large enough to scatter resonantly the photons from the surface.[4] The main reason, which leads the authors to this conclusion, is that the required electron number density $n_{\rm e} \sim 10^{13}\,{\rm cm}^{-3}$ is of two orders larger than the Goldreich–Julian density $n_{\rm GJ} \sim 5 \times 10^{11}\,{\rm cm}^{-3}$. However, although pulsar magnetospheres are unknown in a certain level, it is a common point that primary pairs with Lorentz factor $\gamma_{\rm p} \sim 10^6$ and with density $\sim n_{\rm GJ}$ are accelerated in gaps while more secondary pairs with Lorentz factor $\gamma_{\rm s} \sim 10^{2-4}$ are created outside the gaps.[12] In spite of the fact that the net charge density could be $n_{\rm GJ}$, the absolute number density should be $\sim 10^{2-4}$ times of $n_{\rm GJ}$, which should be enough to scatter the photons effectively from the stellar surface. Actually, this could be another possibility for cyclotron absorptions in the magnetosphere even if no fossil disc contributes a braking torque.

4. The atomic transition of once-ionized helium may be responsible to these lines, although the authors have not presented a full discussion in this possibility[4]. However, in this interpretation, they assume a general field with superstrong strength $B \simeq 1.5 \times 10^{14}$ G, which is much larger than the derived field $B_{\rm e} = 3 \times 10^{12}$ G.[4] It is difficult to understand that this "neutron" star with a *typical* field $B_{\rm e}$ can have such a strong prevalent multipole field on the surface.

Certainly, the discovery of Sanwal *et al.*[4] is very important in both the possibilities: the mass and radius may be derived if the absorption is atomic transition originated, or the accretion rate in the propeller phase could be estimated, for the first time, in the case of two cyclotron lines (point 1).

Mereghetti *et al.*[5] found that the absorption features are phase-dependent: the ~ 1.4 keV line prefers to appear during the minimum and the rising parts, rather than at the peak of the pulse profile. This observational property may reflect the geometry of resonant cyclotron emission: there is almost only one fundamental line for an observer along the magnetic fields, while more harmonic lines appear if the line-of-sight is perpendicular to the fields (Fig. 3 of Ref. [10]). An effort to fit the observed spectrum of 1E 1207.4-5209 was tried by Hailey and Mori,[13] who presumed that the star has an atmosphere with He-like oxygen or neon in not too high field; whereas an elaborate model calculation, to fit in terms of cyclotron resonance lines, is also necessary to know the details of the source.

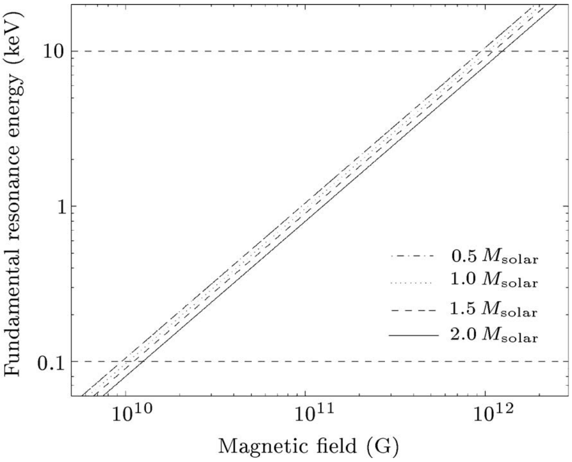

Fig. 1. Energy of the fundamental resonance cyclotron as a function of stellar magnetic fields for bare strange stars with masses of $0.5M_\odot$, $1.0M_\odot$, $1.5M_\odot$, and $2.0M_\odot$, respectively, from the top to the bottom. The hatched range is from 0.1 keV to 10 keV, photons with energy in the range can be collected effectively in *Chandra* and *XMM-Newton* detectors. The region hatched by the two horizontal dashed lines is from 0.1 keV to 10 keV, photons with energy in 0.1–10 keV can be collected effectively in *Chandra* and *XMM-Newton* detectors.

A very interesting and important question is: why is 1E 1207.4-5209 the only one in which the significant absorption features have been detected so far? To answer this question, Mereghetti *et al.*[5] suggested that 1E 1207.4-5209 has a metal atmosphere, which is not old enough to accrete a hydrogen layer. However, this question may naturally be answered alternatively by the selective effect in observations, since only a few sources may have magnetic fields being suitable for creating cyclotron lines with energies in the detector energy range. The fundamental electron cyclotron resonance lies at $\Delta E = 11.6B_{12}\sqrt{1-R_{\rm s}/R}\,{\rm keV}$, where B_{12} is the polar magnetic field in $10^{12}\,{\rm G}$, $R_{\rm s} \equiv 2GM/c^2$ is the Schwarzschild radius, and M and R are the stellar mass and radius, respectively. For a bare strange star with certain mass M, one can obtain its radius R by integrating numerically the TOV equation, with the inclusion of the equation of state for strange matter: $P = (\rho - 4B)/3$ (B is the bag constant). The fundamental resonance energy as a function of magnetic field for strange stars with different masses is shown in Fig. 1. We can see that for detectors (*Chandra* or *XMM-Newton*) from ~ 0.1 to $\sim 10\,{\rm keV}$, the sensitivity fields in which electrons can absorb resonantly photons within that energy range are from $9 \times 10^9\,{\rm G}$ to $1 \times 10^{12}\,{\rm G}$. It is well known that pulsars tend to have a magnetic field of $\sim 10^{12}\,{\rm G}$ (normal pulsars) or of $\sim 10^8\,{\rm G}$ (millisecond pulsars); thus it is unsurprising that only a few sources are observed to show spectral lines. *No source* listed in the table[3] has definitely a suitable field (it may be possible that cyclotron lines could be related to the column accretion process above a stellar surface since such previously discovered lines are from accreting binary systems).

Recently, a 5-keV absorption feature has been detected and confirmed in the bursts of a soft-gamma-repeater SGR 1806-20,[14,15] which is believed to be the feature as one of the proton cyclotron lines in superstrong magnetic field ($\sim 10^{15}\,{\rm G}$) by the authors. However, there are some difficulties in this explanation. (1) Due to the high mass-energy ($\sim 1\,{\rm GeV}$) of a proton, the ratio of the oscillator strength of the first harmonic to that of fundamental in $10^{15}\,{\rm G}$ is *only* $\sim 10^{-6}$! It is unreasonable to detect the first and the *even* higher harmonics. In fact, numerical spectrum simulations of atmospheres with protons in superstrong fields have never shown more than two proton absorption lines.[16,17] (2) A better and more reasonable model for the continuum spectrum component is needed to identify such absorption features in reality. Motivated by these flaws, we suggest that the possible absorption lines at ~ 5, ~ 11.2, and $\sim 17.5\,{\rm keV}$ could be interpreted as electron cyclotron lines, while the $\sim 7.5\,{\rm keV}$ absorption might be caused by other effects (e.g., can the accreting plasma with ions absorb at $\sim 7.5\,{\rm keV}$?). The much smaller ratio $\sim 10^{-7}$ of oscillation strength cannot also be large enough to produce a second harmonic of α particle at $\sim 7.5\,{\rm keV}$. SGR 1806-20 may have an ordinary magnetic field, $\sim 5\times10^{11}\,{\rm G}$, which should be another pulsar-like compact stars with suitable magnetic fields for the detectors in the sky.

Strange stars could exist; the exotic surface of a bare strange star might eventually result in the identification of them, especially the most probable one RX J1856.[18,3] Although each of the observed phenomena from pulsar-like stars may be interpreted under the regime of traditional neutron star with unusual or artificial physical properties, it might be a natural way to understand the observations by updating "neutron" stars with (bare) strange stars.

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