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# DISCOVERY OF ABSORPTION FEATURES IN THE X-RAY SPECTRUM OF AN ISOLATED NEUTRON STAR

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## ABSTRACT

We observed 1E 1207.4−5209, a neutron star in the center of the supernova remnant PKS 1209−51/52, with the ACIS detector aboard the *Chandra X-Ray Observatory* and detected two absorption features in the source spectrum. The features are centered near 0.7 and 1.4 keV; their equivalent widths are about 0.1 keV. We discuss various possible interpretations of the absorption features and exclude some of them. A likely interpretation is that the features are associated with atomic transitions of once-ionized helium in the neutron star atmosphere with a strong magnetic field. The first clear detection of absorption features in the spectrum of an isolated neutron star provides an opportunity to measure the mass-to-radius ratio and to constrain the equation of state of the superdense matter.

*Subject headings:* pulsars: individual (1E 1207.4−5209) — stars: neutron — supernovae: individual (PKS 1209−51/52) — X-rays: stars

## 1. INTRODUCTION

Although neutron stars (NSs) have been studied extensively for more than three decades, the properties of the superdense matter in their interiors still remain an enigma. We know neither the density nor the composition of an NS core. We are not even sure that NSs are indeed composed of neutrons—for instance, their cores could be pion or kaon condensates or a quark-gluon plasma. A key observational property that would help us understand the true nature of these objects is the mass-radius relation—if we knew the masses and radii for a sample of NSs, we could compare them with the predictions of models based on various equations of state of the superdense matter, which are quite different for NSs of different composition (see Lattimer & Prakash 2001 for details). A useful constraint can be obtained via measuring the gravitational redshift $z$ of lines in the spectrum of thermal radiation emitted from the NS surface (atmosphere), which directly gives the mass-to-radius ratio: $M/R = (c^2/2G)[1-(1+z)^{-2}]$. However, many attempts to detect spectral lines in thermal radiation from isolated (nonaccreting) NSs have been unsuccessful. For example, no spectral lines have been found in the spectra of the Vela pulsar (Pavlov et al. 2001), the anomalous X-ray pulsar 4U 0142+61 (Juett et al. 2002), and the nearby radio-quiet NS RX J1865−3754 (Burwitz et al. 2001; Drake et al. 2002), despite sensitive observations with the *Chandra* grating spectrometers. In this Letter, we report the first firm detection of absorption features in the spectrum of an isolated NS, 1E 1207.4−5209.

The pulsar 1E 1207.4−5209, a radio-quiet central source of the supernova remnant (SNR) PKS 1209−51/52 (also known as G296.5+10.0), was discovered by Helfand & Becker (1984) with the *Einstein Observatory*. Mereghetti, Bignami, & Caraveo (1996) and Vasisht et al. (1997) interpreted the *ROSAT* and *ASCA* spectra of 1E 1207.4−5209 as blackbody (BB) emission of $T \simeq 3$ MK from an area with radius $R \simeq 1.5(d/2\ \mathrm{kpc})$ km. Zavlin, Pavlov, & Trümper (1998) interpreted the observed spectra as emitted from a light-element (hydrogen or helium) atmosphere. For an NS of mass 1.4 $M_\odot$ and radius 10 km, they obtained an NS surface temperature $T_{\mathrm{eff}} = 1.4$–$1.9$ MK and a distance $d = 1.6$–$3.3$ kpc, consistent with the distance to the SNR, $d = 2.1^{+1.8}_{-0.8}$ kpc from the neutral hydrogen absorption measurements (Giacani et al. 2000).

Zavlin et al. (2000) observed 1E 1207.4−5209 with the *Chandra X-Ray Observatory* and discovered a period of about 424 ms, which proved that the source is an NS. The second *Chandra* observation provided an estimate of the period derivative, $\dot{P} \sim (0.7$–$3) \times 10^{-14}$ s s$^{-1}$ (Pavlov et al. 2002b). This estimate implies that the characteristic age of the NS, $\tau_c \equiv P/(2\dot{P}) \sim 200$–$1600$ kyr, is much larger than the 3–20 kyr age of the SNR (Roger et al. 1988), while the conventional magnetic field, $B \equiv 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G $= (2$–$4) \times 10^{12}$ G, is typical for a radio pulsar. Spectral analysis of these *Chandra* observations, which resulted in the discovery of two absorption features in the NS spectrum, is presented below.

## 2. OBSERVATION AND DATA ANALYSIS

*Chandra* observed 1E 1207.4−5209 on 2000 January 6–7 and 2002 January 5–6 with the spectroscopic array of the Advanced CCD Imaging Spectrometer (ACIS) in the continuous clocking mode. This mode provides the highest time resolution (2.85 ms) available with ACIS by means of sacrificing spatial resolution in one dimension. The source was imaged on the back-illuminated chip S3. The effective exposure times of the two observations were 29.3 and 31.6 ks, with detector temperatures of −110°C and −120°C, respectively. In both observations, the source+background spectrum was extracted from a segment of 4″ length centered at the source position; the background was taken from 20″ segments in the one-dimensional images. The source count rates after background subtraction are $0.76 \pm 0.01$ and $0.64 \pm 0.01$ s$^{-1}$ in the first and second observations, respectively. The background contributes only about 3% of the total count, in the 0.4–5 keV energy band. The lower count rate in the second observation can be attributed to the reduction of the ACIS sensitivity at low energies with time, apparently caused by increasing deposition of a contaminant onto the ACIS filter.[3]

The continuum models (BB, power law, and fully ionized NS atmosphere) failed to fit the source spectrum, which deviates very significantly from any of the models in a 0.5–2.0 keV range, showing two absorption features near 0.7 and 1.4 keV. Another

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[3] See the *Chandra* X-ray Center Web page http://asc.harvard.edu/cal/Links/Acis/acis/Cal_projects/index.html.

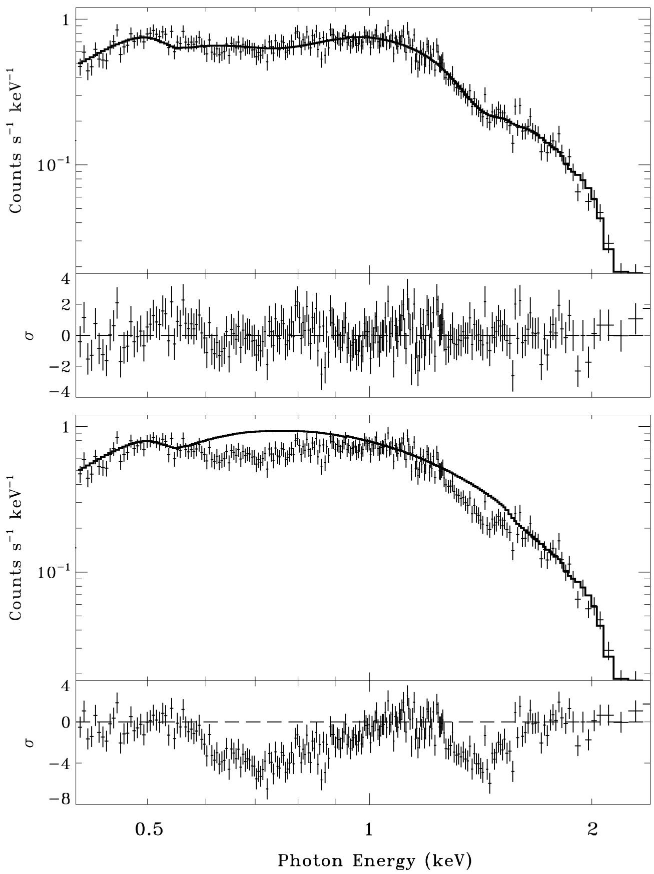


FIG. 1.—*Top panel*: Observed count spectrum and the best fit with the first model (eq. [1]) for the 2000 January observation. *Bottom panel*: Data and the continuum model.

absorption feature observed near 2 keV remains uncertain because of the calibration uncertainty near the Ir M line from the telescope mirror coating, so we do not consider this feature further. We verified that the features at 0.7 and 1.4 keV are not due to uncertainties in the responses and background subtraction and concluded that they are intrinsic to the source. We also checked that no spectral features at these energies are seen in other *Chandra* observations with the same observational setup (e.g., observations of PSR B1055−52 and B0656+14).

To characterize the absorption features, we use the spectral range from 0.4 to 2.5 keV and model the continuum as an absorbed BB with a temperature of $kT = 0.26$ keV. Since we do not know the exact nature of the observed features, we use three phenomenological models to check how sensitive the feature parameters are to the choice of model:

Lines produced by an absorbing layer with Gaussian profiles of absorption coefficients:

$$F(E) = F_c(E) \prod_{i=1,2} \exp\left\{-\tau_i \exp\left[-\frac{(E-E_i)^2}{2\Gamma_i^2}\right]\right\}, \quad (1)$$

multiplicative absorption lines with Gaussian profiles:

$$F(E) = F_c(E) \prod_{i=1,2} \left\{1 - r_i \exp\left[-\frac{(E-E_i)^2}{2\Gamma_i^2}\right]\right\}, \quad (2)$$

and lines with Gaussian profiles subtracted from the continuum:

$$F(E) = F_c(E) - \sum_{i=1,2} F_c(E_i) r_i \exp\left[-\frac{(E-E_i)^2}{2\Gamma_i^2}\right]. \quad (3)$$

In these models, $F_c(E)$ is the continuum spectrum, $E_i$ and $\Gamma_i$ are the central energy and Gaussian width of the $i$th line, respectively, and $\tau_i$ and $r_i$ are the parameters characterizing the line depth [$\tau_i$ is the optical depth at the line center, and $r_i = 1 - F(E_i)/F_c(E_i)$ is the relative line depth, when the lines do not overlap, $|E_2 - E_1| \gg \Gamma_i$].

An example of the fit to the 2000 January data with the first model (eq. [1]) is demonstrated in the upper panel of Figure 1. The lower panel shows the continuum model from the upper panel and the residuals to demonstrate the profiles of the two absorption features. Including the lines in the spectral model improves the quality of the fit substantially: $\chi^2_\nu = 1.05$ for 232 degrees of freedom (dof) versus $\chi^2_\nu = 2.5$ for 238 dof. We find similar improvement in the fit quality for each of the line models for both observations.

The fitting parameters for the models (eqs. [1]–[3]) are presented in Table 1. The continuum normalization, $R = (1.64 \pm 0.02)(d/2.1\ \mathrm{kpc})$ km, is essentially the same for all of the models for both observations. On the contrary, the hydrogen column density $n_\mathrm{H}$ is substantially larger in the second observation. We interpret this as the result of an increased contamination of the ACIS in the second observation that reduces the effective area at lower energies (see footnote 3) and can be crudely modeled as an additional interstellar absorption (i.e., the $n_\mathrm{H}$ parameter does not represent the true interstellar absorption).

TABLE 1

FITTING PARAMETERS FOR THREE MODELS FOR TWO OBSERVATIONS OF 1E 1207.4−5209

| Model | $n_{\mathrm{H},20}$ | $E_1$ (eV) | $\tau_1$ | $\Gamma_1$ (eV) | $W_1$ (eV) | $E_2$ (eV) | $\tau_2$ | $\Gamma_2$ (eV) | $W_2$ (eV) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 2000 January | | | | | |
| 1 …… | 2.33 ± 0.44 | 750 ± 10 | 0.39 ± 0.03 | 125 ± 13 | 108 ± 12 | 1432 ± 10 | 0.45 ± 0.04 | 105 ± 12 | 102 ± 14 |
| 2 …… | 2.28 ± 0.45 | 749 ± 10 | 0.41 ± 0.03 | 134 ± 14 | 112 ± 14 | 1432 ± 10 | 0.46 ± 0.04 | 112 ± 14 | 104 ± 13 |
| 3 …… | 2.34 ± 0.44 | 727 ± 12 | 0.40 ± 0.06 | 127 ± 22 | 108 ± 15 | 1401 ± 12 | 0.43 ± 0.06 | 112 ± 24 | 103 ± 13 |
| | | | | 2002 January | | | | | |
| 1 …… | 7.55 ± 0.54 | 735 ± 14 | 0.29 ± 0.03 | 94 ± 20 | 64 ± 11 | 1423 ± 10 | 0.49 ± 0.04 | 125 ± 14 | 129 ± 14 |
| 2 …… | 7.49 ± 0.54 | 734 ± 14 | 0.30 ± 0.03 | 100 ± 21 | 68 ± 13 | 1422 ± 10 | 0.50 ± 0.04 | 134 ± 16 | 130 ± 16 |
| 3 …… | 7.48 ± 0.54 | 721 ± 17 | 0.30 ± 0.05 | 98 ± 36 | 66 ± 14 | 1380 ± 13 | 0.47 ± 0.07 | 131 ± 26 | 129 ± 18 |

NOTE.—The "optical depth" $\tau_i$ characterizes the line flux with respect to the continuum at the line center; for the second and third models, it is defined as $\exp(-\tau_i) \equiv r_i$ (see eqs. [2] and [3]). The errors quoted are the formal 1 $\sigma$ uncertainties of the fits. The reduced $\chi^2_\nu$-values are within the range of 1.03–1.06 (232 dof for the first observation and 236 dof for the second observation).

The line parameters for the first and second models (eqs. [1] and [2]) are very close to each other within one observation. The third model (eq. [3]) results in somewhat lower central energies. The equivalent widths of the lines, calculated as $W = \int_{E_{\min}}^{E_{\max}} [1 - F(E)/F_c(E)]\, dE$ ($E_{\min} = 0.5$ and 1.1 keV, and $E_{\max} = 1.1$ and 2.5 keV, for the 0.7 and 1.4 keV lines, respectively), are virtually the same for the three models in a given observation.

For a given model, the parameters of the 1.4 keV line are almost the same (within 1.2 $\sigma$) for the two observations. The 0.7 keV line shows an apparent decrease of the central energy, width, and equivalent width. We attribute this to the effect of CCD contamination (see footnote 3) that results in an artificially large $n_{\rm H}$ and distorts the parameters of the line. Since the contamination was presumably insignificant in 2000 January, we believe that the parameters inferred from the first observation give a more adequate description of the lines.

For the empirical line models used, the best-fit models show residuals suggestive of asymmetric and/or multiple lines. Since the spectral resolution of the detector, about 100 eV at these energies, is comparable to the model line widths $\Gamma_i$, each of the observed features can be fitted equally well with multiple line models, with smaller intrinsic line widths. The observed broad features could also be produced as a result of a nonuniform magnetic field on the surface of the rotating NS.

Reanalysis of the previous X-ray observations of this source has shown no features in the *ROSAT* Position Sensitive Proportional Counter and *ASCA* Gas Imaging Spectrometer spectra, which can be readily explained by the very poor spectral resolution of these proportional counters. The spectrum acquired with the *ASCA* Solid-State Imaging Spectrometer (a CCD imaging spectrometer) does show features at the same energies, albeit at low significance due to insufficient statistics. The spectral models with two lines, which fitted the *Chandra* spectra, are consistent with the *ROSAT* and *ASCA* spectra.

## 3. DISCUSSION

Attempts to explain the absorption features as being caused by the intervening interstellar (or circumstellar) material lead to a huge overabundance for some elements. For instance, the absorption feature at 1.4 keV might be interpreted as a magnesium photoionization edge at $E = 1.305$ keV. The fit of this feature with a photoionization edge model gives the best-fit edge energy of 1.29 keV, not that strongly different from the Mg K edge. However, to explain the strength of absorption, this model requires an Mg abundance about 600 times the solar value. The energy of the other feature, 0.7 keV, is close to the F K$\alpha$ (0.67 keV) and Mn L$\alpha$ (0.64 keV) energies, but an even larger overabundance of these elements would be needed to explain the observed feature. Therefore, the absorption in the interstellar medium looks improbable, and the observed features are most likely intrinsic to the NS. There are two potential ways for these absorption features to be generated in the NS atmosphere: cyclotron lines and atomic transition lines.

### 3.1. *Cyclotron Lines*

First we consider that the observed features are cyclotron lines produced in a strongly ionized NS atmosphere. If one assumes that these are electron cyclotron lines, the features could be interpreted as the fundamental and the first harmonic of the electron-cyclotron energy $E_{\rm ce} = 1.16 B_{11}$ keV in a magnetic field $B_{11} \equiv B/(10^{11}\ {\rm G}) \sim 0.6(1+z)$ or as two fundamentals emitted from two regions with different magnetic fields, $B_{11} = 0.6(1+z)$ and $1.2(1+z)$, broadened by the radiative transfer effects and/or nonuniformity of the magnetic field. However, it is difficult to reconcile this interpretation with the expected strength of the surface magnetic field. The measured $P$ and $\dot{P}$ imply a magnetic moment $\mu \sim (3Ic^2 P\dot{P}/8\pi^2)^{1/2} \sim 3 \times 10^{30} I_{45}^{1/2}$ G cm$^3$, where $I = 10^{45} I_{45}$ g cm$^2$ is the moment of inertia. This magnetic moment corresponds to a magnetic field $B_e \sim 3 \times 10^{12}$ G at the magnetic equator, if the field is a centered dipole and the NS radius is $R = 10$ km. If the dipole is off-centered, or if there are substantial multipole components, the maximum values of the surface magnetic field would be even higher. Although the inferred value of $B_e$ is based on $\dot{P}$ estimated from two observations under the assumption of a uniform slowdown (no glitches, no timing noise, and the NS is not in a binary orbit), the discrepancy of the fields looks uncomfortably large. In addition, the oscillator strength of the first harmonic is smaller than that of the fundamental by a factor of $\sim E_{\rm ce}/(m_e c^2) \sim 2 \times 10^{-3}$ (at $E_{\rm ce} \gg kT$; Pavlov, Shibanov, & Yakovlev 1980), so that it is hard to explain why the 1.4 keV feature is as strong as the 0.7 keV feature if we assume the two lines are associated with the same magnetic field.

The magnetic fields of $\sim 10^{11}$ G should exist within the NS magnetosphere, and the resonant cyclotron scattering in such magnetic fields could absorb (scatter) ~1 keV photons emitted from the NS surface (e.g., Rajagopal & Romani 1997). In a dipole magnetic field, $B(r) = B_e(1 + 3\cos^2\theta_B)^{1/2}(R/r)^3$, the resonant scattering of photons with energy $E$ occurs at a distance from the NS surface $r \approx 3.7R(B_e/3 \times 10^{12}\ {\rm G})^{1/3} \times (E/0.7\ {\rm keV})^{-1/3}(1 + 3\cos^2\theta_B)^{1/6}$, where $\theta_B$ is the magnetic colatitude. To produce a line with a width $\delta E$, the thickness of the scattering layer should be $\delta r \sim \frac{1}{3}(\delta E/E)r$; i.e., $\delta r \lesssim 0.03r \sim 1$ km for the observed $\delta E/E \lesssim 0.1$. It is not clear how two narrow layers (an analog of the Van Allen radiation belts in the Earth's magnetosphere?) could be formed. Moreover, the electron number density needed to obtain a sufficient optical thickness $\tau$, $n_e \sim 10^{13}(\tau/0.5)\ (R/10\ {\rm km})^{-1}(E/0.7\ {\rm keV})^{4/3}(B_e/3 \times 10^{12}\ {\rm G})^{-1/3} \times (1 + 3\cos^2\theta_B)^{-1/6}$ cm$^{-3}$, significantly exceeds the Goldreich-Julian density, $n_{\rm GJ} \sim 5 \times 10^{11}$ cm$^{-3}$, often adopted as a reasonable estimate for the charge density in the NS magnetosphere. Therefore, this hypothesis does not look very plausible.

Alternatively, one can assume that the spectral features are associated with ion-cyclotron energies, $E_{\rm ci} = 0.63(Z/A)B_{14}$ keV, where $Z$ and $A$ are the ion's charge and mass numbers, respectively. The surface magnetic field needed for this interpretation is $\gtrsim 10^{14}$ G, much larger than the conventional magnetic field inferred for a centered dipole from the $P$, $\dot{P}$ measurements. However, if the magnetic dipole is off-centered to about 3 km below the surface, the magnetic moment $\mu = 3 \times 10^{30}$ G cm$^3$ gives a surface field of about $10^{14}$ G. We cannot exclude the possibility that the true period derivative is significantly larger than that estimated from the two observations (e.g., due to strong glitches), which would increase the inferred magnetic field. However, the ion-cyclotron interpretation of the observed features is not straightforward, even in such a strong magnetic field. An explanation of two features as the fundamental and first harmonic of an ion-cyclotron line is unrealistic because the ratio of the harmonic and fundamental oscillator strengths, $\sim E_{\rm ci}/m_i c^2$, is extremely low. One could explain the two lines as being produced by different ions, with $(Z_1 A_2)/(Z_2 A_1) = 2$. For instance, one might assume that the 1.4 and 0.7 keV lines are due to protons ($Z/A = 1$) and $\alpha$-particles ($Z/A = \frac{1}{2}$), respectively, in a magnetic field $B_{14} = 2.2(1+z)$. The problem with this interpretation is that the strengths of the lines require similar abundances of hydrogen and helium, which is hard to sustain because of element sedimentation in the strong gravitational field of the NS. To avoid this problem, one could assume that the radiation emerges from a purely helium, partially ionized atmosphere—then the 1.4 keV line would be due to helium nuclei in $B_{14} = 4.4(1 + z)$, while the 0.7 keV line would be caused by ion-cyclotron transitions of once-ionized helium ions ($Z/A = \frac{1}{4}$). The required field, however, is so strong that it is hard to expect a significant fraction of fully ionized helium at the effective temperature of about 3 MK inferred from the spectral continuum (the temperature may be even lower if one applies NS atmosphere models). In addition, such cyclotron transitions should be accompanied by atomic transitions in, at least, once ionized helium.

### 3.2. *Atomic Lines*

The other possibility is that the observed features are atomic lines formed in the NS atmosphere. The available nonmagnetic NS atmosphere models do not fit the observed spectrum, which is not surprising because the observed pulsations require a strong magnetic field. In recent years, there has been significant work on the structure and spectra of atoms in strong magnetic fields, mostly in fields below $10^{13}$ G (see, e.g., Ruder et al. 1994, Mori & Hailey 2002, and references therein). Based on these works, we can exclude some possibilities. For instance, the observed absorption features cannot be explained as emerging from a hydrogen atmosphere because at any magnetic field and any reasonable gravitational redshift, there is no pair of strong hydrogen spectral lines whose energies would match the observed ones. Therefore, one has to invoke heavier elements. A possible interpretation of the observed features as being due to atomic transitions of once-ionized helium in a strong magnetic field, $B \approx 1.5 \times 10^{14}$ G, has been suggested by Pavlov et al. (2002a); detailed modeling of the spectrum will be presented in a forthcoming paper. This interpretation yields the gravitational redshift $z = 0.12$–$0.23$, which corresponds to $R/M = 8.8$–$14.2$ km $M_{\odot}^{-1}$. In that interpretation, the 0.7 keV feature is a single line while the 1.4 keV feature may include several lines that cannot be resolved with the ACIS. To confirm this, one should investigate the detailed structure of the detected strong features with a high-resolution spectrometer and detect other (weaker) helium lines.

## 4. CONCLUSION

The discovery of the absorption features in the spectrum of 1E 1207.4−5209 provides the first opportunity to measure the mass-to-radius ratio and the magnetic field of an isolated NS. Measuring $M/R$ is particularly important because it can constrain the equation of state of the superdense matter in the NS interiors, infer the internal composition of NSs, and test the theories of nuclear interactions. Our analysis of the low-resolution spectra has shown that interpreting the observed features as cyclotron lines requires artificial assumptions, and such features cannot be explained as being formed in a hydrogen atmosphere. The energies of the features suggest that they could be associated with the atomic transitions of once-ionized helium in an atmosphere with a strong magnetic field. This interpretation yields a gravitational redshift of about 0.17. To firmly identify the features and measure the gravitational redshift with better accuracy, deep observations with high spectral resolution are needed, such that would be able to resolve potentially multiple lines blended together as a result the low spectral resolution of the CCD detector.

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