PROCEEDINGS OF SCIENCE

4U 1538−522: An Increasing Cyclotron Line Energy with Time

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We present the first evidence for the increase in cyclotron resonance scattering feature centroid energy with time for an accreting X-ray binary, 4U 1538−522. The increase occurs monotonically over the last two decades. This is in contrast with that of Her X−1, the first accreting X-ray binary to show a decrease in CRSF energy with time over a similar period of time, and the first to show any secular trend with time. The change in energy implies a decrease in height above the neutron star surface for the scattering region, or an increase in the local magnetic field strength. One possible explanation is a change in the local shape/strength of the magnetic field near the surface due to an imbalance between matter accreted into the accretion column and matter escaping from the base of the column.

10th INTEGRAL Workshop: A Synergistic View of the High-Energy Sky
15-19 September 2014
Annapolis, MD, USA

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†We thank Dr. Katja Pottschmidt, for organization and enlightening discussions. We also thank NASA for support of PH.

PoS(Integral2014)025

1. Accretion Column X-ray Spectra

Neutron stars with $\sim 10^{12}$ Gauss magnetic fields in orbit around high mass stellar companions accrete matter from the stellar winds, and channel the matter to the magnetic poles. Once under the influence of the predominately dipole field, the infalling matter forms an accretion column above the poles. Within the column three processes are involved in varying amounts, depending on the mass accretion rate. Blackbody radiation is emitted from the heated neutron star surface and/or the mound of accreted matter at the base of the column (Figure 1). Bremsstralung emission is produced in the interaction of the blackbody photons with the infalling relativistic electrons and protons. Cyclotron emission is generated by the electrons spiraling around the neutron star magnetic field. All of these photons undergo Compton up-scattering with the hot electrons in the column. This complex set of interactions has defied detailed, physics-based modeling until recently (Becker & Wolff , 2007), and only empirical models of the continuum have been used in spectral modeling of the observed spectra.

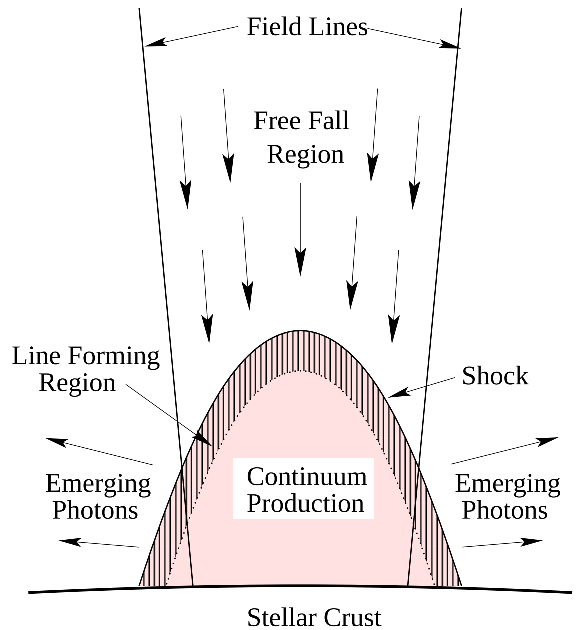

Figure 1: An illustration of the concept of an accretion column with accretion mound at the base (Heindl et al. , 2004).

The structure of the accretion column can vary significantly with accretion rate. At the lowest accretion rates, no shock is formed and the mound is somewhat disk shaped at the neutron star surface. In this case the optical depth is low in the upward direction and a pencil X-ray beam is formed. At somewhat higher accretion rates, a collisional shock forms above the surface and the mound is more cylindrical with the optical depth lower towards the sides than upwards. In this case a fan beam from the sides is preferred. A further increase in accretion moves the shock lower towards stronger magnetic field strength regions. Above some critical accretion rate, as expressed as a luminosity, a radiation dominated shock forms due to the high X-ray flux from below. Again the geometry is cylindrical and a fan beam emission pattern is expected, but here an increase in accretion rate causes the radiative shock to move to higher altitudes, where the magnetic field is weaker.

2. Cyclotron Resonant Scattering Features (CRSFs)

Electrons in a uniform magnetic field can travel freely along the magnetic field lines, but are constrained to circular motion when traveling perpendicular to the magnetic field. This helical motion can be observed in the laboratory, where the moving electrons circle in a magnetic field with the Larmor frequency. For very strong magnetic fields, such as fields close to the neutron star surface, the gyration radius becomes similar to the de Broglie wavelength, so that quantum effects become non negligible. In such a regime, the perpendicular motion of the electrons is quantized and is described by individual Landau levels. For a magnetic field less than the critical field (4.4×10^{13} Gauss), the energy between two Landau levels is described by the cyclotron energy: $E_{\rm cyc} \approx 11.6 \times B_{12}$ keV, where B_{12} is the magnetic field in units of 10^{12} Gauss.

Measuring the mean energy of the cyclotron line can then be used to calculate the magnetic field strength in the vicinity of the neutron star. A photon with the cyclotron energy $E_{\rm cyc}$ can interact with an electron in the magnetic field by exciting the electron from its present Landau level to the next level. The electron de-excites back to its original Landau level shortly after by emitting a photon a random direction. Because only a small fraction of the photons are emitted along the original line of sight, an outside observer measures a lack of photons at the cyclotron energy. This appears as an absorption-like feature in the continuum spectrum, commonly referred to as a Cyclotron Resonance Scattering Feature (CRSF) or cyclotron line. Photons with sufficiently high energy can excite an electron into a higher energy state, which then de-excites through different Landau levels in a cascade of multiple photons. The presence of multiple Landau levels can lead to multiple CRSF features in a spectrum, as seen in the outburst of 4U 0115+63 (Figure 2). The exact location of the CRSF scattering region in the accretion column is uncertain and strongly depends on the accretion geometry, accretion rate and other parameters. As indicated in Figure 1, it is generally assumed that the CRSF is created in the outer layers of the accretion mound or column where the optical depth to Compton scattering is lowest.

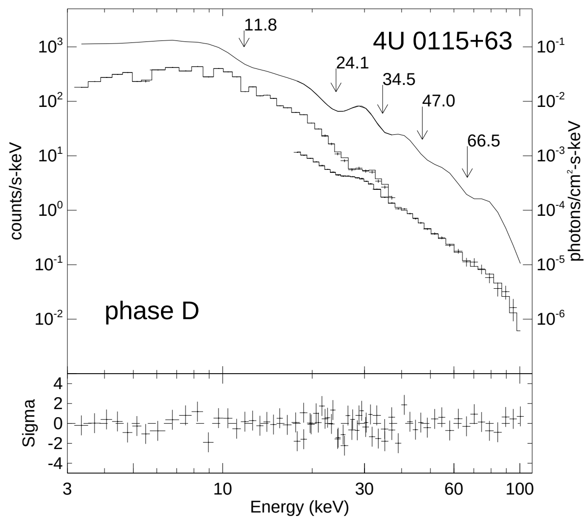

Figure 2: The X-ray spectrum of 4U 0115+63 near outburst maximum. Five CRSF features are seen. (Heindl et al. , 2004)

3. 4U 1538−522

4U 1538−522 is an accreting neutron star pulsar in a binary system with the 15−20 $M_\odot$ B0Iab supergiant, QV Nor (Reynolds et al. , 1992).The system has a ∼526 s pulse period. The orbital period is 3.73 days (Becker et al. , 1977; Davison et al. , 1977), however the eccentricity is a matter of debate. Originally, Clark et al. (1990) reported both a circular (e=0) and an e=0.17 value. This has not been resolved, but Rawls et al. (2011) state that no physical analytic solution can be found for an eccentric orbit with its reported eclipse duration due to the system's high inclination. They go on to report results for both orbits, and find masses of the neutron star of less than 1 $M_\odot$. The distance to 4U 1538−522 is 6.4±1.0 kpc (Reynolds et al. , 1992). The persistent X-ray luminosity is $\sim 4 \times 10^{36}$ ergs/s. This luminosity places it in the collision-dominated regime of the accretion column, which would predict an increase in the CRSF energy with luminosity. Since the discovery of the CRSF in 4U 1538−522 at ∼22 keV by Clark et al. (1990), all missions with hard X-ray capability have measured it (Hemphill et al. , 2014, and references therein). As noted below, the exact measured value of the CRSF centroid energy depends upon the details of the spectral modeling, and using a specific model for all of the modern measurements (*RXTE, INTEGRAL*, and *Suzaku*) is the subject of this paper.

4. CRSF Measurements Pre-Suzaku and Pre-RXTE Re-analysis

4U 1538−522 has been observed with instrumentation capable of detecting and measuring the CRSF at 20-25 keV and possibly the overtone at higher energies. The discovery was made by *Ginga* (Clark et al. , 1990) and confirmed by a second *Ginga* observation (Mihara et al. , 1998). Since then the source has been observed by *RXTE* (Coburn , 2002), *BeppoSAX* (Robba et al. , 2001), and *INTEGRAL* (Rodes-Roca et al. , 2009). The spectra from these various observations were modeled by different empirical models for the continuum, as well as either a Gaussian or Lorentzian shaped absorption feature. The choice of models results in small but not unnoticeable differences in the reported CRSF energy. These previous measurements of the CRSF energy are shown in Figure 3 as a function of luminosity. The expected increase with luminosity is not seen, but the error bars and scatter in values make detecting such an effect difficult.

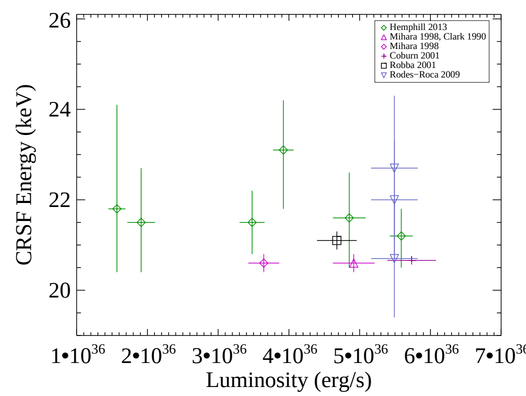

Figure 3: Past measurements of the CRSF in 4U 1538−522 made with differing spectral models.

5. Consistent Analysis of Modern Data

Four empirical continuum models are typically used for spectral analysis: a power law with a high energy cutoff (`power*highecut`), a power law modified by an exponential (`cutoffpl`), a Fermi-Dirac modification of a power law (`power*fdcut`), and the negative-positive exponential (`NPEX`). These models fit the observed continuum from accreting pulsars relatively well, but have no parameters which reflect the physical processes involved. Additionally, different

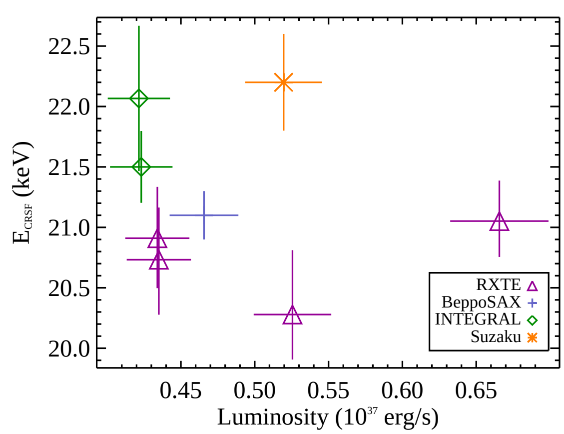

Figure 4: Results from the consistent analysis of the modern observations of the CRSF in 4U 1538−522 .

authors use different models, making a detailed comparison of results difficult. In order to have a consistent set of measurements, we have re-analyzed all of the *RXTE* data, including some not contained in Coburn (2002), along with data from *INTEGRAL* (Hemphill et al. , 2013), and a recent *Suzaku* observation (Hemphill et al. , 2014). Since the *BeppoSAX* analysis used the same spectral model, the published values were used. We have used a continuum model of a power law with a high energy cutoff (`powerlaw*highecut`) and a Gaussian shape for the CRSF (`gabs`), with an iron line at 6.4 keV and low energy absorption, where applicable. The plot of the CRSF centroid energies versus luminosities from the re-analyzed spectra are shown in Figure 4, where again a trend with luminosity is not seen.

6. CRSF vs Time

When one plots the CRSF energy versus time for the modern observations that have consistent spectral analysis, a clear increase in the CRSF energy with time is evident (Figure 5 *Left*). A least squares fit to the data yields a slope of 0.087±0.049 keV/yr at 3σ confidence. This is the first evidence for an increase in the CRSF centroid energy with time in any accreting X-ray pulsar. The direct implication is that the scattering region is moving to higher magnetic field regions. It might be argued that this trend is partially due to an as-yet undetected correlation between luminosity and CRSF energy, as is the case in Her X-1 (Staubert et al. , 2014). However, when one corrects the measured CRSF energies for the trend in time, the CRSF energy vs luminosity plot remains flat (Figure 5 *Right*). Thus, we argue that 4U 1538−522 represents the first instance of an increasing CRSF energy with time.

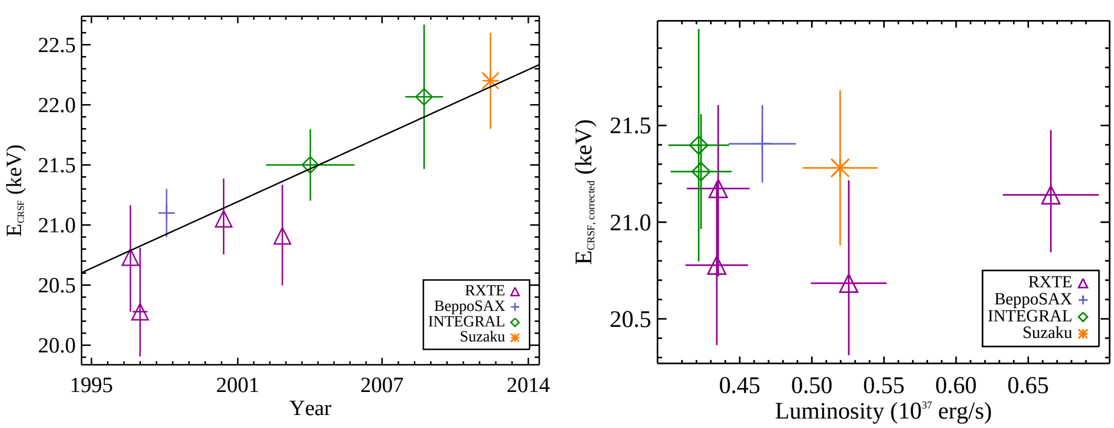

Figure 5: *Left*: The CRSF energy versus time over almost two decades. *Right*: The CRSF corrected for the trend with time plotted versus luminosity. No apparent trend is seen, although the error bars are relatively large.

7. Discussion and Summary

RXTE, INTEGRAL, BeppoSAX, and *Suzaku* measurements of the CRSF centroid energy in the accreting binary pulsar 4U 1538−522 show a significant increase in the centroid with time over the past two decades, and yet does not show an expected, contemporaneous, upward trend in luminosity. Another accreting X-ray pulsar, Her X−1, shows the opposite trend as recently reported by Staubert et al. (2014). The CRSF centroid energy for Her X−1 was relatively stable throughout the 1970s and early 1980s, and then, when observation resumed in the late 1990s, it had increased by nearly 20%, at which point it began a slow decrease over the next two decades. Her X−1 does show a positive correlation with luminosity, indicating that it is in the sub-critical luminosity regime, as is 4U 1538−522.

One possible explanation that would explain the general features of both systems' variation with time is the balance between the amount of matter accreted (i.e. added to the accretion mound) and the amount of accreted matter being drained from the mound (R. Staubert pvt. comm.). In the case of 4U 1523−522, the drain is faster than the input, thus reducing the height of the mound and thus sampling a higher field region near the magnetic poles. For Her X−1, the infalling material dominates and the mound grows with the scattering region sampling lesser field strengths. Another idea involves the accretion mound exerting a force on the dipole field, distorting it at the poles. Then the amount of distortion could be time variable and dependent on the rate of accumulation or drainage of matter. In any case, 4U 1538−522 and Her X−1 are providing exciting, new, behaviors that challenge the understanding of neutron stars and their magnetic fields.

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