Chandra Observations of the GC M28 and its ms-Pulsar PSR 1821-24

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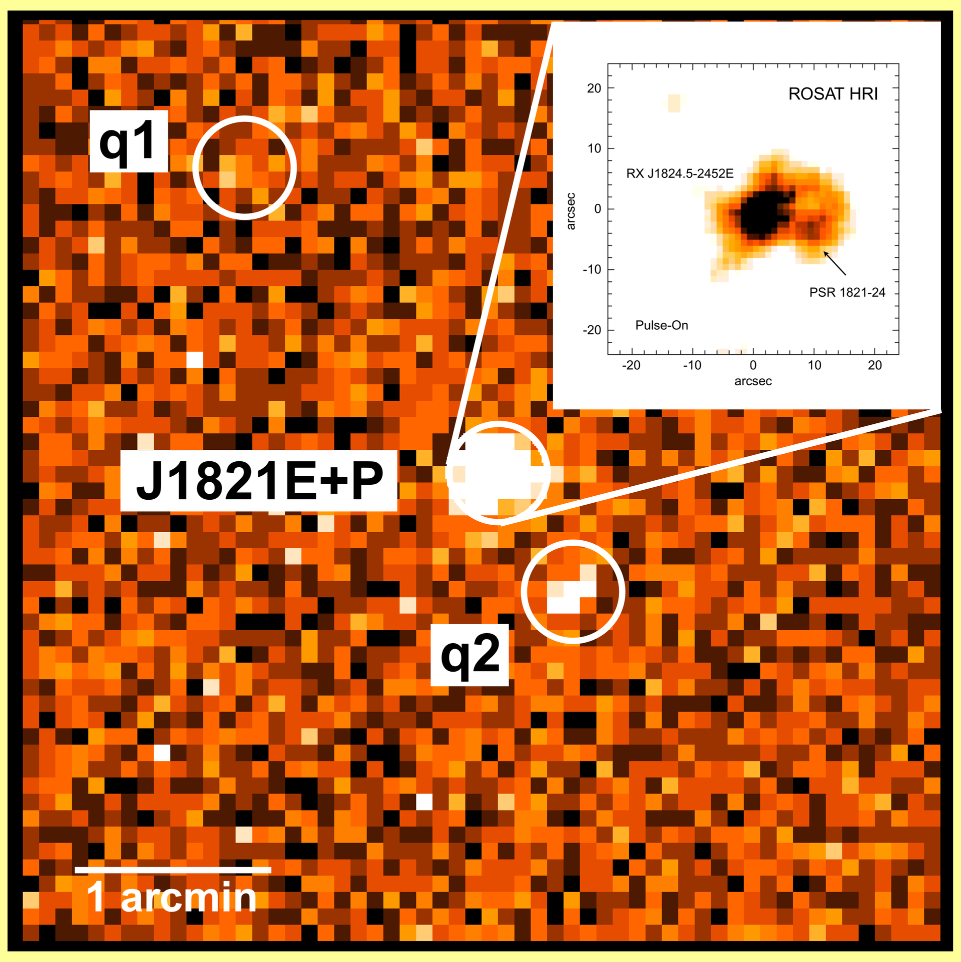
Abstract: We report on results of the first Chandra observations of the globular cluster M28 (NGC 6626). The observations detected 46 X-ray sources in M28, of which 12 lie within one core radius of the center. The observations show that the apparently extended X-ray core emission seen with the ROSAT HRI is due to the superposition of multiple discrete sources of which almost 30% are variable. One of the main goals of the observations was to measure the unconfused phase-averaged X-ray spectrum of the 3.05-ms pulsar B1821-24. We find that the pulsar spectrum is best described by a power law with photon index ~1.2, with marginal evidence of an emission line centered at 3.3 kev. Interpreting the line feature in terms of cyclotron emission from a corona above the pulsar's polar cap suggest that the magnetic field is ~100 times stronger than deduced from the magnetic braking model for a centered dipole. The unabsorbed pulsar flux in the 0.5 - 8.0 keV band is ~3.5 x E-13 ergs/s/cm^2. In addition to the pulsar spectrum we present X-ray spectra of the 5 brightest unidentified X-ray sources. Based on the spectral parameters the brightest of these sources is suggested to be a transiently accreting neutron star in a low-mass X-ray binary in quiescence. In addition to the resolved sources the Chandra observations reveal fainter, unresolved Xray emission from the central core of M28.

ROSAT images of the globular cluster M28 (NGC 6626)

Since the Einstein era it has been clear that globular cluster contain various populations of X-ray sources of very different luminosities. The stronger sources ($L_X \sim 10^{36}$ - 10^{38} erg s^{-1}) were seen to exhibit X-ray bursts, which led to their identification as low-mass X-reay binaries. The nature of the fainter sources, with $L_X < 3 \times 10^{34}$ erg s^{-1}, however, was more open to discussion. Although many weak X-ray sources were detected by ROSAT (see Verbunt 2001 for a review), their identification has been difficult because of low photon statistics and source confusion.

The first ms-pulsar detected in a globular cluster was PSR 1821-24 (Lyne et al. 1987). This solitary pulsar has a rotation period of P =3.05 ms and a period derivative of $\dot{P}$ =1.61 x 10^{18} s s^{-1}. The inferred pulsar parameters make PSR 1821-24 the youngest ($P/2\dot{P}$= 3.0 x 10^7 yr) and most powerful ($\dot{E}$= 2.24 x 10^{36} erg/s) pulsar among all millisecond pulsars. The inferred magnetic diploar field at the pulsar's magnetic pole is B_p= 4.5 x 10^9 G. Although this is ~ 3 orders of magnitude less than what is observed in ordinary field pulsars, it is the strongest magentic field observed among the group of ~ 100 known millisecond pulsars.

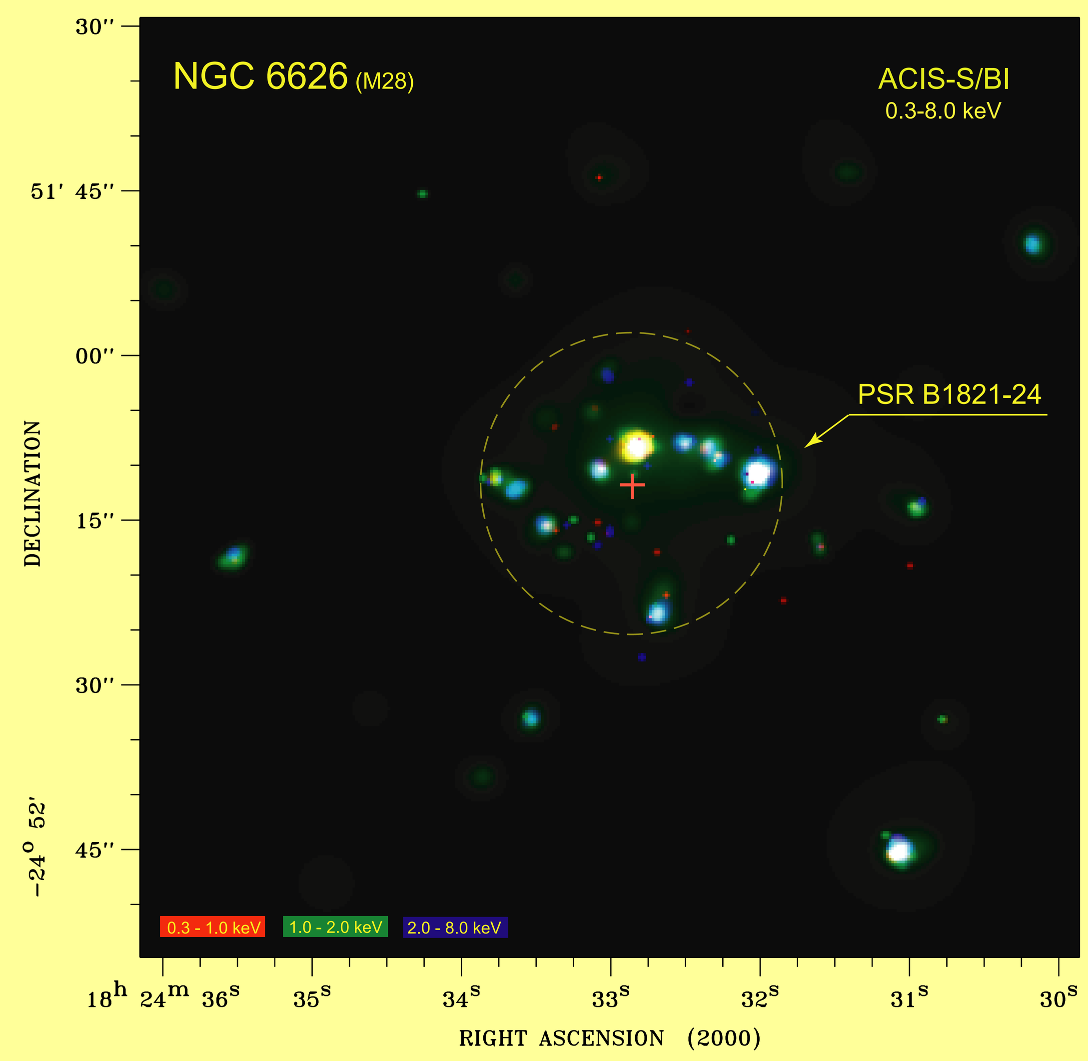


The image above shows a 5' x 5' field of the central part of M28, combining 80 ksec HRI data taken between 1991-1997. Indicated are the position of four ROSAT sources (J1824E, J1824P, q1 and q2). The circle q1 indicates the PSPC position for this source which is undetected by the HRI. The upper-right inset magnifies the core encompassing J1824E+P. To create this inset the HRI data were oversampled at 1"/bins and temporally phased to emphasize "pulse-on" events from the ms-pulsar PSR 1821-24 (denoted as J1824P). Whether the apparent extended and diffuse emission of J1821E was from a pulsar powered synchrotron nebula, due to a pulsar-wind interaction with the intra-cluster gas in M28 or whether it just was due to unresolved globular cluster sources was the question to be investigated in our Chandra observations (cf. right image).

The ROSAT HRI observations further made clear that X-ray spectral information from the millisecond pulsar taken with ASCA, RXTE or BeppoSAX suffer from spectral contamination from nearby sources, especially in the soft band below 10 keV. The high spatial resolution of the Chandra ACIS instruments was thus supposed to provide the first uncontaminated pulsar spectrum and energy flux in the 0.5 - 8 keV X-ray band.

Chandra ACIS image of the globular cluster M28

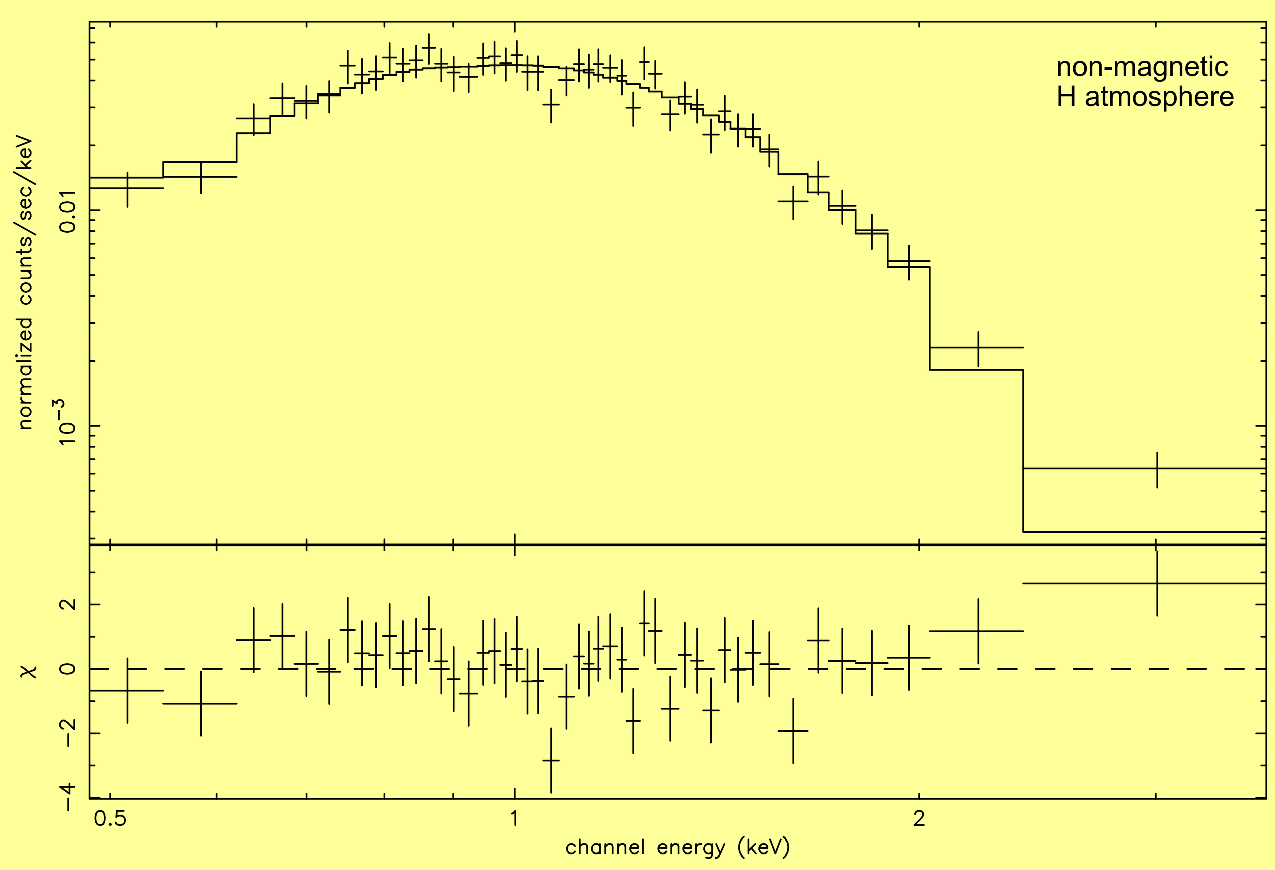
M28 was observed three times for approximately equal observing intervals of about 13 ksec between 2002 July and September. These observations were scheduled so as to be sensitive to time variability on time scales up to weeks. The observations were made using ACIS-S2, S3 and S4 CCDs in faint timed exposure mode with frame time of 3.241s and thus provide spectro-imaging information but no timing information from the ms-pulsar PSR 1821-24.



The resulting S3 image, combining the data from the ~ 38 ksec observations, is shown on the right. Different colours correspond to the respective energy bands. Twelve X-ray sources are detected within the 0'.24 core radius, indicated by a dashed circle. 46 sources are detected within a 3.1 arcmin extraction radius (of which ~10 sources might be unrelated to the cluster). About 30% of the sources were found to be variable on time scales of hours to weeks. The brightest source in the data, located near to the optical cluster center, is found to have the softest X-ray spectrum among all detected cluster sources (cf. boxes below). The ms-pulsar PSR 1821-24 is the hardest X-ray source in the cluster. Its X-ray counterpart is in agreement with being a point source, i.e. no extended diffuse emission from a pulsar-wind nebula is detected. The apparently extended X-ray core emission seen in the ROSAT HRI thus is due to the superposition of multiple discrete sources. However, closer inspection of the ACIS data shows that , in addition to the resolved sources, fainter unresolved X-ray emission from the central core of the cluster is detected. Pooly et al. (2002) found similar unresolved emission in the central regions of the CXO image of the globular cluster NGC 6440.

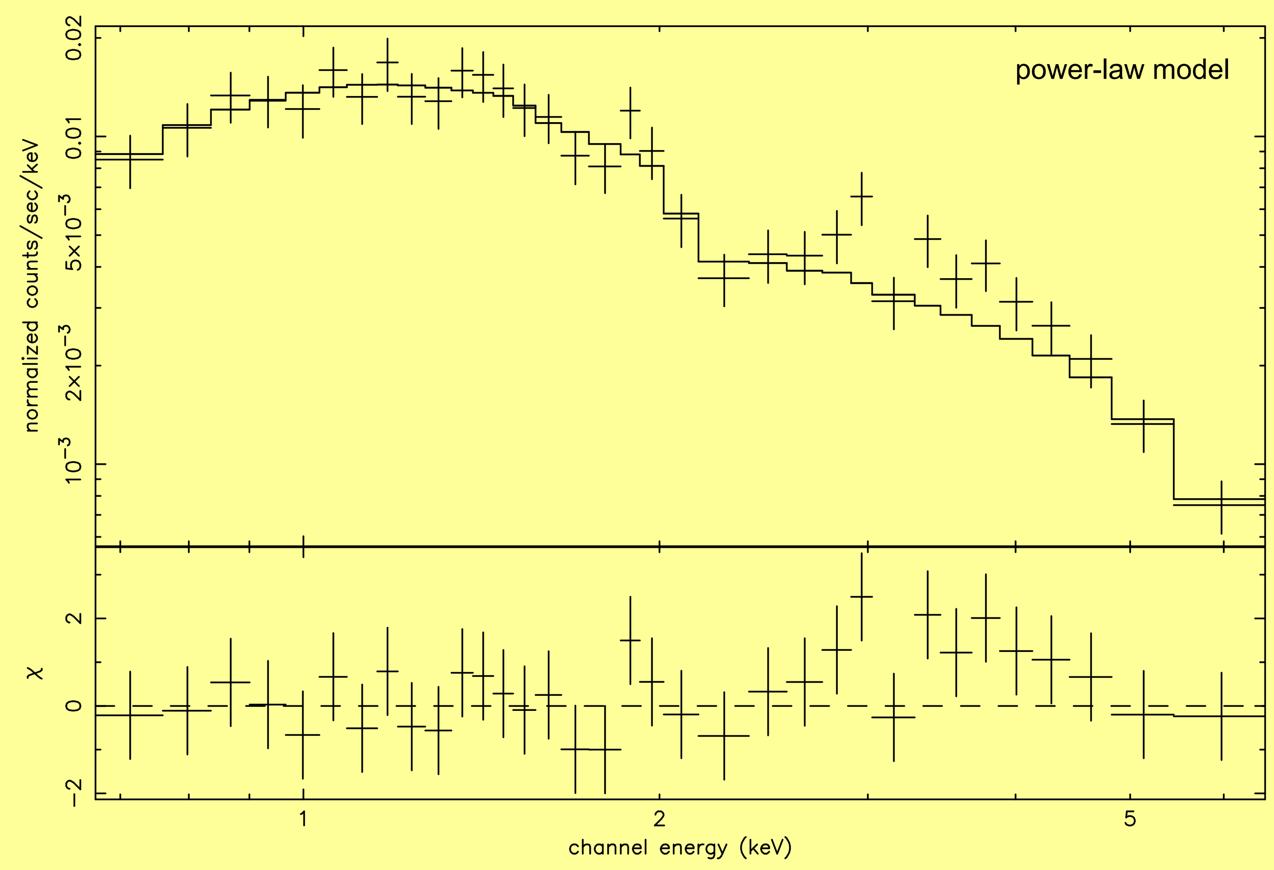
Fitting the projected surface density of the detected X-ray sources to a King profile allowed us to determine the core radius to be ~ 11". This is comparable to the core radius of 14" as deduced from the distribution of optical light from the cluster (Harris 1996). Assuming that the dominant visible stellar population has a mass of $M_* \sim 0.7\ M_\odot$ we find that the best-fit mass of the X-ray sources is M_X = 1.87 (+1.25, -0.49) $M_\odot$, following the derivation of Grindlay et al. (2002)

The spectrum of the brightest X-ray source in the globular cluster M28



Of particular interest among the brightest X-ray sources detected in M28 is the luminous soft source located near to the optical center of globular cluster. A blackbody fit gives the hydrogen column density $N_{22} \sim 0.13$, a temperature $kT_{BB} \sim 0.26$ keV and a radius $R_{BB} \sim 1.3$ km, corresponding to the bolometric luminosity of $L_{BB} \sim 10^{33}$ erg/s. Such values are typical for blackbody fits of LMXB with ransiently accreting neutron stars in quiescence. The relatively high temperature can be explained by heating of the neutron star crust during the repeated accretion outbursts. The radius R_{BB} is much smaller than expected for a neutron star. A likely reason is that the BB-model is inappropriate to describe the thermal radiation from the neutron star surface. Fitting a neutron star atmosphere spectral model (Zavlin eta l 1996) yields R_{NS}=14.5 (+6.9,-3.8) km and the effective temperature T_{eff} = 90 (+30, -10) eV for an assumed neutron star mass of 1.4 $M_\odot$.

The phase averaged spectrum of the millisecond pulsar PSR 1821-24



The spectrum was measured by extracting ~1100 counts within a radius of 1.72 arcsec centered on the pulsar position. The data were binned into 34 bins guaranteeing at least 30 counts/bin. A power-law model with a column density of N_{22}=0.16 (+0.07, -0.08) and a photon-index of 1.2 (+0.15, -0.13) yields the best fit. The residuals hint a spectral feature or features at an energy slightly above 3 keV. By adding a Gaussian "line" to the power-law model we found a line center at 3.3 keV with a Gaussian width of 0.8 keV and a strength of ~ 6 x 10^{-6} photons cm^{-2} s^{-1} which corresponds to a luminosity of ~ 1.1 x 10^{31} erg/s. Assuming that the feature is real and considering an electron cyclotron line then it would mean that it is formed in a magnetic field of strength B ~ 3 x 10^{11} G. Although this is about a factore 100 higher than the magnetic field deduced from the magnetic braking model, such strong field can be explained by the presence of either multipolar components or a strong-offcentering of the magnetic pole, or both.

References:

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Full results of the data analysis as well as full observational details can be found in

astro-ph/0211468

and in the recent issue of

ApJ 594: p798 - 811