Searching For The Rarest Stars In Our Galaxy

University of Sussex

Announcing the discovery of eleven Isolated Neutron Star candidates - potentially doubling the number currently known. By Heather Campbell.

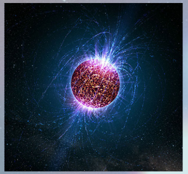
Project shortlisted for SET Physics Student of the Year Award 2009

Why looking for these sorts of stars is interesting

The mystery of the missing stars

There are more than 1000 billion stars in our Galaxy but so far we have only found seven in a rare category known as radio silent isolated neutron stars (INS). They are so precious to astronomers that they have been nicknamed "The Magnificent 7". Searching for INS is like looking for a four leaf clover - you have to look at thousands of similar objects before you find one. I looked at 6860 objects and only found 11 INS candidates!

Some stars are bigger than others. When a really massive star exhausts its nuclear fuel supply, it undergoes an enormous explosion (supernova*). The outer layers are blown away and remaining material collapses under gravity until the protons and electrons fuse to form a *neutron star*.



Artist's impression of a neutron star

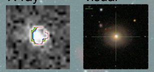
Neutron stars usually occur in binary systems however *isolated neutron stars* (INS) exist on their own. They start off being bright sources at several different wavelengths (e.g. visual, radio and X-ray) but over time they lose their energy and end up only being detectable with X-ray telescopes.

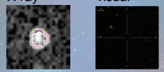
Artist's impression of a neutron star

INS are characterised by thermal black-body emission*. Theories predict that INS are hot (several million degrees Kelvin) and give off at least 1000 times as much energy at X-ray wavelengths, compared to the visual. Astronomers use this characteristic X-ray to optical flux ratio to identify new INS candidates.

Theory also predicts that about a million INS should be easily detectable from Earth. So it is an enduring mystery as to why only 7 have been discovered so far. Perhaps we haven't been looking in the right places (or in the right way)? Or perhaps we don't understand the physics of neutron stars as well as we thought and our models are wrong. The only way to resolve the mystery is to find more objects to study. Identification of new INS is crucial in order to understand the relationships between different classes of neutron stars and to test theories.

To get an idea of how we find INS, and how rare they are, take a look at the images below. On the left is an X-ray source with an obvious visual counterpart. On the right is an X-ray source with no visual counterpart: according to optical telescopes, that location is blank! You can see that the X-ray images look similar, whereas the visual images are very different. For every source like that on the right, there are 200 sources like that on left!





* See 'Beginner's guide to X-ray astronomy'

Why we looked again

Why our search is special!

The first search for INS was carried out using an X-ray catalogue from ROSAT* (Augus et al. 2004). More recently an XMM* catalogue, the 2XMMp*, has been used to look for these unusual sources. So far only 1 extra, as yet unconfirmed, candidate has been found using XMM (Pires et al. 2009). My search improves on the previous work because I have special access to two state of the art databases:

The XMM Cluster Survey (XCS, Romer et al. 2001) has discovered more than 100,000 X-ray sources. This database is not public and so I am the first person to undertake a search for INS using XCS. The advantages of XCS over 2XMMp for this work include the relative catalogue sizes and source characteristics (in particular the ability of XCS to differentiate between fuzzy and point like X-ray sources; INS will be point like).

The Sloan Digital Sky Survey (SDSS, York et al. 2000) covers approximately ¼ of the sky and has catalogued 1357 million visual objects. I have collaborated with SDSS experts, allowing me to go far beyond the simple catalogue comparisons that have been used in the past to search for INS. For example I have been able to use the SDSS photometric quasar* catalogue sample to check the XCS source positions.

* See 'Beginner's guide to X-ray astronomy'

How we carried out our research

How to search for a needle in a haystack

I was searching for high X-ray to visual flux ratio objects, since they make good INS candidates. So I looked for blank areas in the SDSS that correspond to highly significant objects in the XCS.

One of the key features of my method is the potential to use X-ray spectroscopy to confirm the identity the INS candidates (previous INS searches required additional X-ray telescope time for this step). I confined my search to XCS sources with more than 300 counts (where *counts* is the number of X-ray photons collected during the observation), as this is the lowest number needed to produce X-ray spectra. INS have soft black-body* spectra and so can be separated from other sources, because they have different spectral signatures in the X-rays.

I searched for SDSS blank regions, within a radius of 7.5'' ('' = arc second = 1/36000°) around XCS sources. This search radius is three times larger than the typical positional accuracy of XMM. However some XMM images have larger positional offsets than others, so I confined my search to the 662 XMM images (from a total of 4190) that contain XCS matches to SDSS quasars*, as they have very well defined astrometry (*astrometry* refers to coordinates on the sky).

In addition, I only used XCS sources that fell in well understood parts of their respective XMM image.

After an unexpected category of object ended up in my candidate list (see below), I further refined my search to exclude XCS sources in the vicinity of very nearby galaxies.

I searched around 2179 XCS sources with more than 300 counts, but found only 13 with no match in SDSS.

I checked many other catalogues and web based databases, to see if these 13 sources had counterparts in other wavelengths. Only two had; they had already been classified as active galactic nuclei*, hence I removed them from my sample.

For the remaining 11, I calculated the maximum visual fluxes from the SDSS limiting magnitudes (*magnitude* is an astronomical measure of brightness). I then calculated the minimum X-ray to visual flux ratio for my candidates and was pleased to discover that all of them were in the right range to be viable INS candidates (~100). By comparison the "Magnificent 7" range from 10000 to 100000, so additional optical follow-up will be needed before the candidates are confirmed.

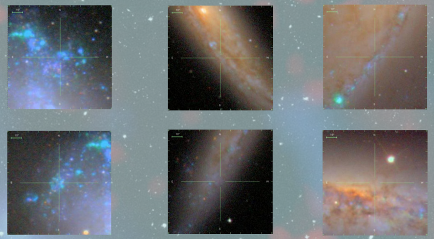
* See 'Beginner's guide to X-ray astronomy'

An Unexpected Result

Accidental discovery of another exciting type of X-ray source

Whilst searching for INS candidates I was shocked to find 36 XCS sources with SDSS images like those shown below. These are certainly not INS!

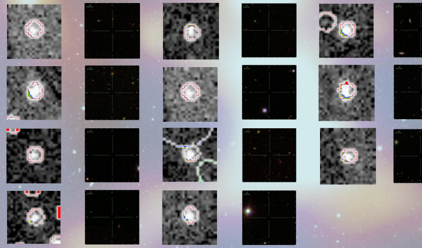
- The X-rays are probably coming from mini black holes in active star forming regions.
- These objects are fascinating to astronomers, because they tell us about black hole properties.
- Many of the black hole sources I found have not been catalogued before and so will be included in my INS discovery paper.
- To exclude them from my INS candidate list I now only select sources that are a sufficiently far from nearby galaxies.



Our candidates

New treasures

Here are the XCS and SDSS images for my 11 new INS candidates:



Comparison with the "Magnificent 7":

- My candidates are brighter (1.3 → 2.8 $\times 10^{-14}$ erg/s/cm^2 compared to 0.2 → 1.1 $\times 10^{-14}$ erg/s/cm^2)
- My candidates were detected with more XMM counts (321 → 750 compared to 22 → 82).

Interpretation: The 11 XCS sources are excellent INS candidates. They are brighter than the "Magnificent 7", so are either younger or closer (or both).

Comparison with a rival XMM study:

- Pires et al. (2009) have just published a complementary search to mine, using the 2XMMp catalogue in the southern hemisphere (my search was in the northern hemisphere).
- They published 8 candidates, of which 7 have already been shown not to be INS (because their flux ratios are 100 or less). The remaining candidate only has 93 XMM counts and so X-ray spectroscopy is not possible without additional XMM observations.

Interpretation: I believe my 11 candidates to be as good as those in Pires et al. This comparison demonstrates the success of the search techniques I developed in collaboration with XCS and SDSS experts.

Conclusions

And what we plan to do next

- In this project I have discovered 11 new INS candidates. This has the potential to more than double the number of known INS. They were identified by locating visually blank areas in the SDSS that correspond to an XCS source.
- INS have extremely high X-ray to visual flux ratios compared to ordinary X-ray sources. Using the SDSS detection limit (of $r > 23.1$), my candidates are ~100 times brighter in X-rays than in visible. Many other databases were checked for alternative counterparts to these new candidates and none were found. This makes them excellent INS candidates.
- All my candidates have sufficient counts to allow X-ray spectra without extra X-ray follow up.

What's next:

- Make X-ray spectra of these 11 candidates. INS have a distinctive soft black-body spectra, so the spectra could help to rule out other types of X-ray sources, such as quasars.
- Carry out deeper visual follow up of these candidates as the SDSS images are not quite deep enough to categorically say that these sources are definitely INS. Deeper visual images will push the limits on the X-ray to visual flux ratio down even further.
- Position corrections could be performed on individual XMM images, because the candidates are detected in fields with SDSS quasars, allowing me to reduce my search radius further (and find even more bright INS candidates).
- XCS already has a selection function for clusters but it would be very interesting to investigate the point source selection function. This will allow us to calculate the volume density of INS and ultimately apply stringent constraints on theory.

Acknowledgements

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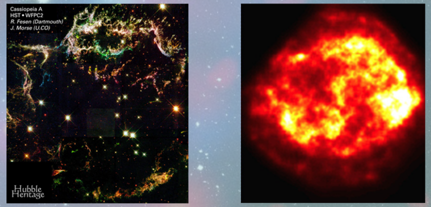
Beginner's guide to X-ray astronomy

- X-ray wavelengths are tiny (~1 millionth of a mm).
- Even though X-rays were first used in medicine in the early twentieth century (the image to the right shows an X-ray of a human hand), X-ray astronomy is still a new subject and discoveries are being made all the time.

- X-rays are absorbed by the earth's atmosphere. Thus space-based observatories are needed to observe X-rays from space. For this reason, X-ray astronomy didn't really get started until the 1980s.
- My project uses the XMM-Newton telescope launched in 1999. Other X-ray satellites include ROSAT and Chandra.
- X-rays are produced if an object is very hot (several million degrees); this is called *black-body emission* (imagine a coal glowing white hot in a fire, if it were heated up several million degrees it would start emitting X-rays). Or if there are charged particles, like electrons, spinning in magnetic fields; this is called *synchrotron radiation* (the Northern Lights are produced by cosmic particles spinning in the Earth's magnetic fields).
- X-rays are emitted by many different astronomical objects including: stars, supernova remnants, active galactic nuclei, quasars and clusters of galaxies.
- X-ray images are fuzzier than visual images because it is much harder to focus high energy photons (as can be seen from the images below).

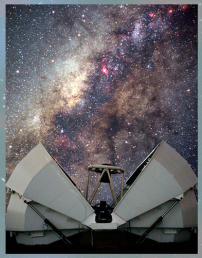


Above: visual and X-ray images of the supernova remnant Cassiopeia A. The visual image, from Hubble Space Telescope (left) shows far more detail, however the X-ray image (right) is still needed because it shows different physics.

How you can get involved

Astronomy is available to everyone

- **You could try to search for these elusive objects yourself!** Both SDSS and XMM allow public access to their databases (just Google "2XMM" and "SDSS" to find them). To obtain the data you require from the database there is an interface that uses SQL querying. This is a simple querying language which allows you to retrieve data. There is a good beginner's tutorial to SQL queries on the SDSS website (Google "SDSS SQL how to").
- **Galaxy Zoo** – Humans are far better than computers at recognising the patterns. So scientists have asked the public to help then classify the millions of galaxies in the SDSS archive. If you fancy joining the team of over 150,000 people working on a genuine research project, check out **www.galaxyzoo.org**.
- **Faulkes Telescope Project** – This project allows school pupils to control the largest robotic telescopes in the world from the classroom. For more information visit **www.faulkes-telescope.com**.
- **Nuffield Science Bursaries** are available to school and college students to get involved in real research projects over the summer. For more information visit **www.nuffieldfoundation.org**.
- **Project Work at University** – I did this project as part of my degree. Make sure you take A2 level maths and physics, so you can go onto study physics or astrophysics at university.



The Faulkes Telescope

***Image credits**: Column 1, 1. http://a52.g.akamaitech.net/f/52/827/1d/www.space.com/images/070820_neutron_star_02.jpg; 2. http://www.dailygalaxy.com/photos/uncategorized/2007/08/21/neutron_star_1_2.jpg. Column 4, 1. http://www.dreamstime.com/royalty-free-stock-photos-x-ray-front-picture-of-the-palm-image1509818; 2. http://hubblesite.org/gallery/album/star/supernova/pr2002015b/; 3. J. A. M. Bleeker et al.: Cas. A, 2001; 4. Composite image of the Faulkes Telescope North in Hawaii, courtesy of Nik Szymanek, www.roe.ac.uk: Background image courtesy of NASA, R. Massey (California Institute of Technology) and ESA, http://xmm.esac.esa.int/external/xmm_science/gallery/public/level3.php?id=388. All other images courtesy XCS or SDSS.*

***References:** Augus et al. 2005, astro-ph/0511659v1; Pires et al. 2009, astro-ph 0812.4151v2; Romer et al. 2001, ApJ, 547, 594; York et al 2000, ApJ,120, 1579.*