Thermally emitting isolated neutron stars in the eROSITA sky

Future Perspectives of Space Science and Space Exploration

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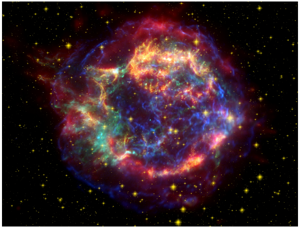
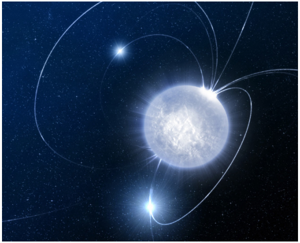
Neutron stars: what we know



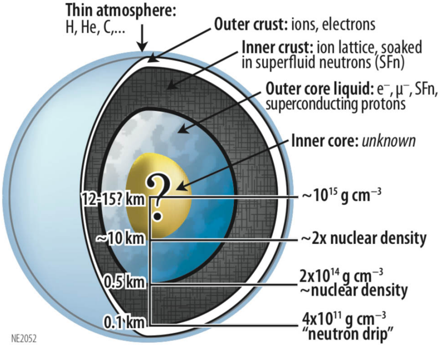


Courtesy: NASA/CXC/ESO

1932	very dense star to hold against gravitational collapse (*unheimliche Sterne*, Landau)
1939	supernova connection (Baade & Zwicky)
1967	fundamental discoveries in radio & X-rays (pulsars, Sco X-1)

- endpoint of the life of a massive star
- densest objects that can be directly observed in the Universe
- also the strongest magnets and the fastest spinning
- all four fundamental forces of Nature are important inside one

What we (do not) know

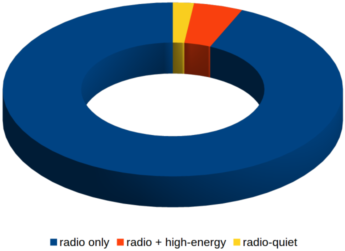


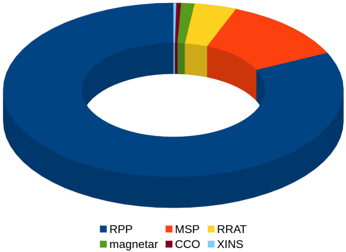
Credit: SAO

- evolution is coupled: magneto-rotational and thermal
- emissivity covers the entire electromagnetic spectrum
- dominant mechanism at a given age is determined by properties inherited at birth and temporal evolution

Theoretical uncertainties: supernova explosion, equation-of-state, effects of mass loss/binarity, fallback accretion?

The neutron star census today



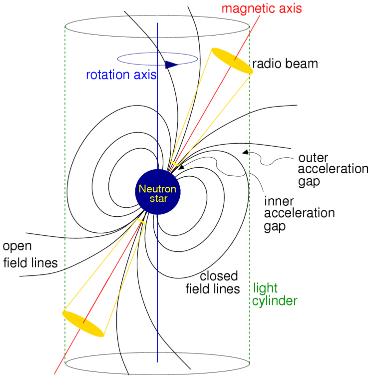


Over 2500 catalogued pulsars

(%)	
98	seen in the radio regime
82	rotation-powered pulsar (RPP)
12	millisecond pulsar (MSP)
4	rotating radio transients (RRAT)
	(erratic and diverse radio sources)
2	magnetars, M7, CCOs
	(peculiar radio- and γ-ray-quiet)

Source: ATNF pulsar database

The magnetic dipole braking model



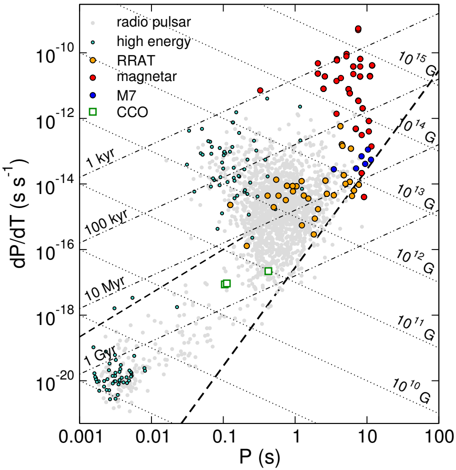
Credit: Lorimer & Kramer

- radio pulse: lighthouse effect
- the star radiates at the expense of its rotational energy
- a gradual lengthening of the period ($\dot{P}$) is observed (typically 3 s/10^8 yr)
- consequence of torque exerted by the magnetic field (and particle acceleration)

Useful estimates of pulsar quantities

- spin-down: $\dot{E} = 4\pi^2 I\dot{P}P^{-3}$
- age: $\tau_{\rm ch} = P(2\dot{P})^{-1}$
- dipolar field: $B_{\rm dip} = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G

Neutron stars in the Milky Way



Radio and γ-ray surveys

- rotation-powered pulsars
- millisecond (recycled) pulsars

Peculiar neutron stars

- escape detection
- challenge evolution theories
  - magnetars
  - the ‘Magnificent Seven’ (M7)
  - central compact objects (CCOs, a.k.a. anti-magnetars)

Radio pulsars do not tell the whole story

The magnetar-M7 connection

Strong fields at birth produce hot and long-period neutron stars due to field decay

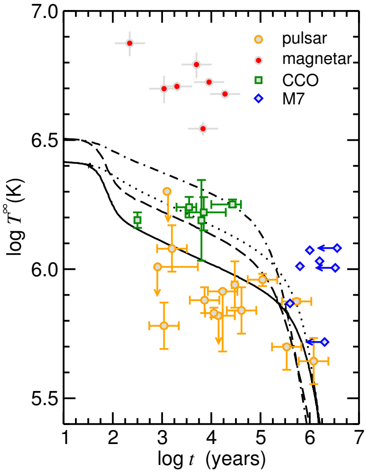
(models by Viganò, Rea, Pons, Aguilera et al.)

CCOs: different outcome of NS evolution

If the NS accretes lots of fallback debris:

- its magnetic field may be buried
- it won't spin down (no radio)
- its cooling rate is affected

(c.f. Chevalier, Muslimov & Page, Geppert, Ho, Bernal, Viganò, . . .)



We need more sources!

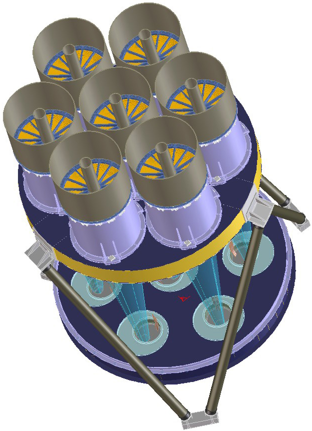
These channels are not probed by radio and γ-ray pulsars

Despite the theoretical development seen in recent years:

- even the state-of-the-art models are built over uncertain assumptions
  (e.g. initial field configuration, level of impurity of the crust)
- known pulsars are not sufficient to constrain models of field decay
  (Gullòn et al. 2015)
- formation and fate of CCOs:
  how common is such an episode in the Galaxy? timescale of field re-emergence?
- . . . plus transients and the unknown!
  (faint AXPs/SGRs, old accreting neutron stars?)

eROSITA on board Spectrum-RG

- orbit around L2
- 4 years all-sky survey
- 3 years pointed observations
- large collecting area and FoV
- seven identical mirror modules
- data split MPE/IKI
  (West/East of the galactic centre)
- launch: September 25, 2017 (shipment to Russia: October 2016)

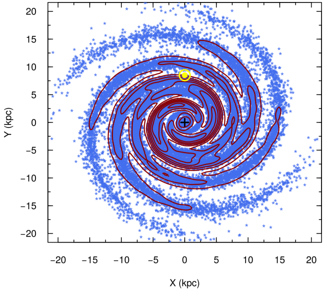


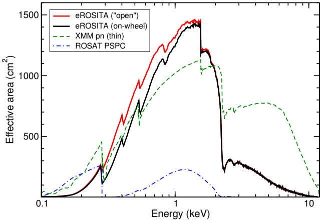
Credit: MPE

Unique potential (for decades to come!) to unveil faint radio-quiet neutron stars and probe the population as a whole

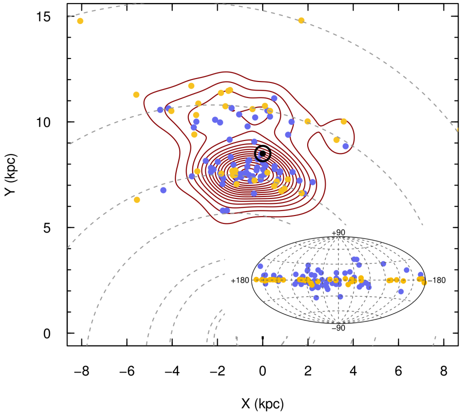
Tracking neutron stars from birth up to present time

- progenitor stars in spiral arms
- interstellar medium (analytical hydrogen layers), abundances, cross-section
- birth properties: spatial velocity, isotropical kick, constant birthrate
- motion integrated in the galactic potential
- thermal evolution: standard cooling (*to be included:* effects of fallback/field decay)
- isotropic blackbody emission
- eROSITA effective area and filters, averaged over FoV, survey exposure
- detection limit of 30 counts (0.2–2 keV)





eROSITA forecast (Pires et al. 2016; in preparation)



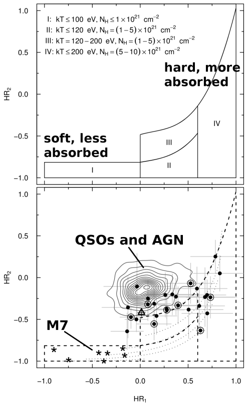
- Simulations give 85 to 100 thermally emitting neutron stars in the survey after 4 yr
- Average distances within 300 pc and 8 kpc (median 2 kpc)
- The minimum flux is $\sim 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$
- The median flux is $\sim 3.5 \times 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$
- 20% of the sources at intermediate flux ($\sim 10^{-13}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$)

Potential for discoveries

Sources at intermediate flux can already be targeted for follow-up in the optical (VLT, LBT) and in X-rays (XMM-Newton, Chandra)

Pinpointing candidates

Cross-correlation, selection in hardness ratio, visual screening, optical follow-up

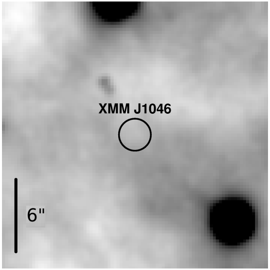


2XMMp: 30 out of 72,000

($f_X > 10^{-14}$ erg s^{-1} cm^{-2})

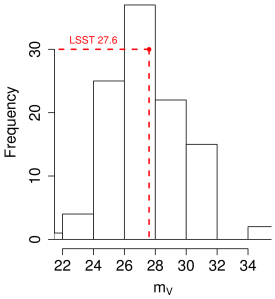
What's the limiting magnitude to rule out ordinary X-ray emitters (AGN/CV/stars)?

Discovery of a NS in Carina



$m_V > 27$ (2σ)

$\log(F_X/F_V) > 3.5$



Follow-up expectations

Taking as reference our past work with the 2XMMp and the NS in Carina:
(2XMM J104608.7-594306, Pires et al. 2009, 2012, 2015)

- efficient selection of 600 candidates with $m_{\rm R} > 21 - 23$
- 5 min/target (8 m class telescope) to rule out CVs/AGN ($m_{\rm V} > 27$)

Assuming 20 neutron stars within the sample of candidates:

- 100 ks (5 ks/target) with Chandra for sub-arcsecond precision
- 2 Msec (100 ks/target) with XMM-Newton to:
  - constrain pulsations down to 15%
  - determine spectral parameters (5% kT, 15% $N_{\rm H}$)
  - detect spectral features or deviations from the thermal continuum

Summary

Peculiar neutron stars	fewer in number, but very important!
eROSITA all-sky survey	ten-fold increase on known sources
Population synthesis + results of the survey	knowledge beyond the Solar vicinity (spatial density, birthrate, alternative evolutionary channels)
Follow-up studies	evolutionary state identify missing links in the NS zoo

Thank you!