# Calvera: An Isolated Compact Object of Indeterminate Type

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# X-ray Observations of Isolated Compact Objects

- Isolated Compact Objects are presumably remnants of stellar evolution.

- Isolated objects are unaffected by the evolution of a binary companion (such as in LMXBs), and they can provide a “pristine” look at the properties of “neutron stars” -- generically, the compact objects which are the result of supernovae at the end of a massive star’s H-burning lifetime.

# Observational Approach

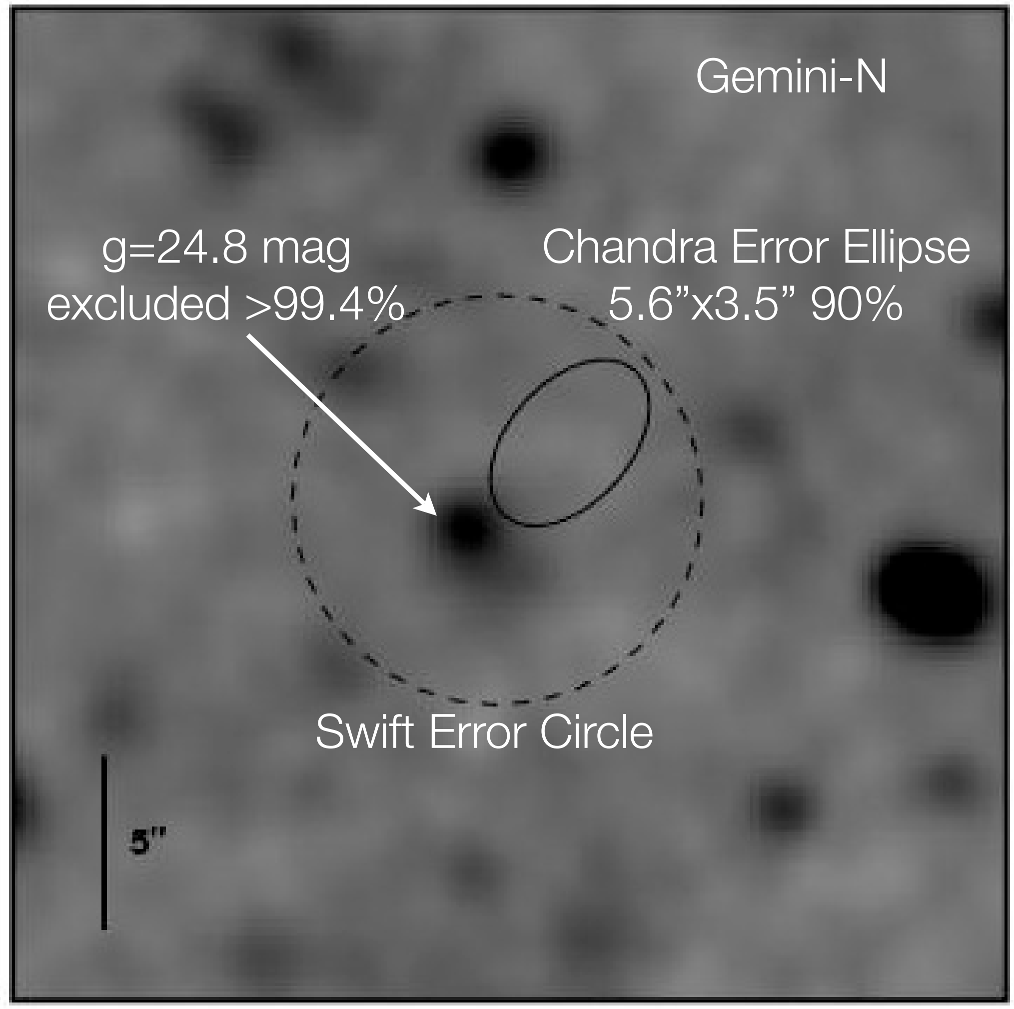
- Perform SWIFT X-ray observation of unidentified ROSAT All-Sky Survey Bright Source Catalog X-ray sources.
- Use better localization (5” with XRT, and <1” if there is a UVOT counterpart) to identify UV, optical, or infrared counterpart (in UVOT image, or 2MASS catalog, or DSS).
- X-ray sources with high F_X/F_UVOT, and no 2MASS or DSS counterparts.
- To date, we have observed ~160 X-ray sources, identifying mostly low-mass stars, a few AGN, but also 3 new X-ray clusters.

# Observations of Calvera

- First detection (1992) in the ROSAT All-Sky Survey as 1RXS J141256.0 +792204.
- We observed with SWIFT/XRT in August 2006, obtained a 5” error circle which excluded all nearby counterparts (DSS, 2MASS, NVSS). No UVOT counterpart (UVM2>21m).
- In Dec 2006, we obtained deep Gemini-North imaging (DDT time) in g-band (2 hours integration) for a limit of g>26.3 mag (3 sigma).
- In early 2007, Chandra/HRC-S DDT observation (2ksec) localized the X-ray source to an error ellipse which excluded all infra-red objects.

# Gemini North Multi-Object Spectrograph.

- Error circles 90% confidence
- Chandra positional uncertainty dominated by statistical uncertainty in off-axis X-ray source, associated with J=9.83 band 2MASS source (3.6" offset?? -- prob=2e-5; Chandra astro-metric calibration uncertain due to recent thermal re-setting).
- FX/F_V > 5100 -- excludes all known source classes other than isolated neutron stars (INSs).



$$L_x = 4\pi\, R_{\rm bb}^2\, \sigma T_{\rm eff}^4$$

# What Type of Source is Calvera?

- The observational approach (arcsec localization, followed by deep optical imaging, to produce high FX/F_V limit) was chosen to find new INSs, like RX J1856.
- No counter examples of high FX/F_V limit objects selected in this way which are not INSs exist in the literature; but clearly it is possible to find other types of compact objects.
- Basis for comparison: assume blackbody spectra (almost certainly not physically true!) and compare bbody spectral parameters.
- Note: to say *anything* about the properties of the source, one must compare either R_bb or L_x with those of a known class. This directly implies a distance to Calvera.
- For INSs -- assume Rbb are all identical to RXJ 1856, and a distance to RXJ 1856 of 170 pc (see Kaplan et al 2007).

# Summary of Properties of SWIFT J1412+7922

Table 1. Characteristics of Calvera

| Characteristic | Value |
|---|---|
| Right Ascension (J2000) | $14^h12^m55^s.51$ |
| Declination (J2000) | $+79°22'06''.7$ |
| Uncertainty ellipse | $5.6'' \times 3.5''$ at P.A. 137.9° |
| UVOT Limit | $f_{UVM2} < 1.3 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ |
| Gemini Limit ($3\sigma$) | $g > 26.3$ mag |
| Blackbody Energy Spectrum | |
| $kT_{eff}$ | $220^{+45}_{-40}$ eV |
| Normalization | $5.4^{+2.7}_{-1.9}$ $(R_{km}/D_{10kpc})$ |
| Corrected X-ray Flux | $7.6\times10^{-13}$ (erg cm$^{-2}$ s$^{-1}$; 0.1–2.4 keV) |
| $N_H$ (fixed) | $3\times10^{20}$ cm$^{-2}$ |
| $\chi^2_\nu$ (dof; prob) | 0.09 (2 dof; prob=0.92) |
| Power Law Energy Spectrum | |
| Photon Slope $\alpha$ | $3.2^{+0.5}_{-0.4}$ |
| Corrected X-ray Flux | $7.9\times10^{-14}$ (erg cm$^{-2}$ s$^{-1}$; 2-10 keV) |
| $N_H$ (fixed) | $3\times10^{20}$ cm$^{-2}$ |
| $\chi^2_\nu$ (dof; prob) | 2.71 (2 dof; prob=0.06) |

# Galactic Distribution of X-ray "Dim" Isolated Neutron Stars (INS), if Calvera is like them.

Table 2. Galacto-centric Positions of INSs and Calvera in an INS Interpretation

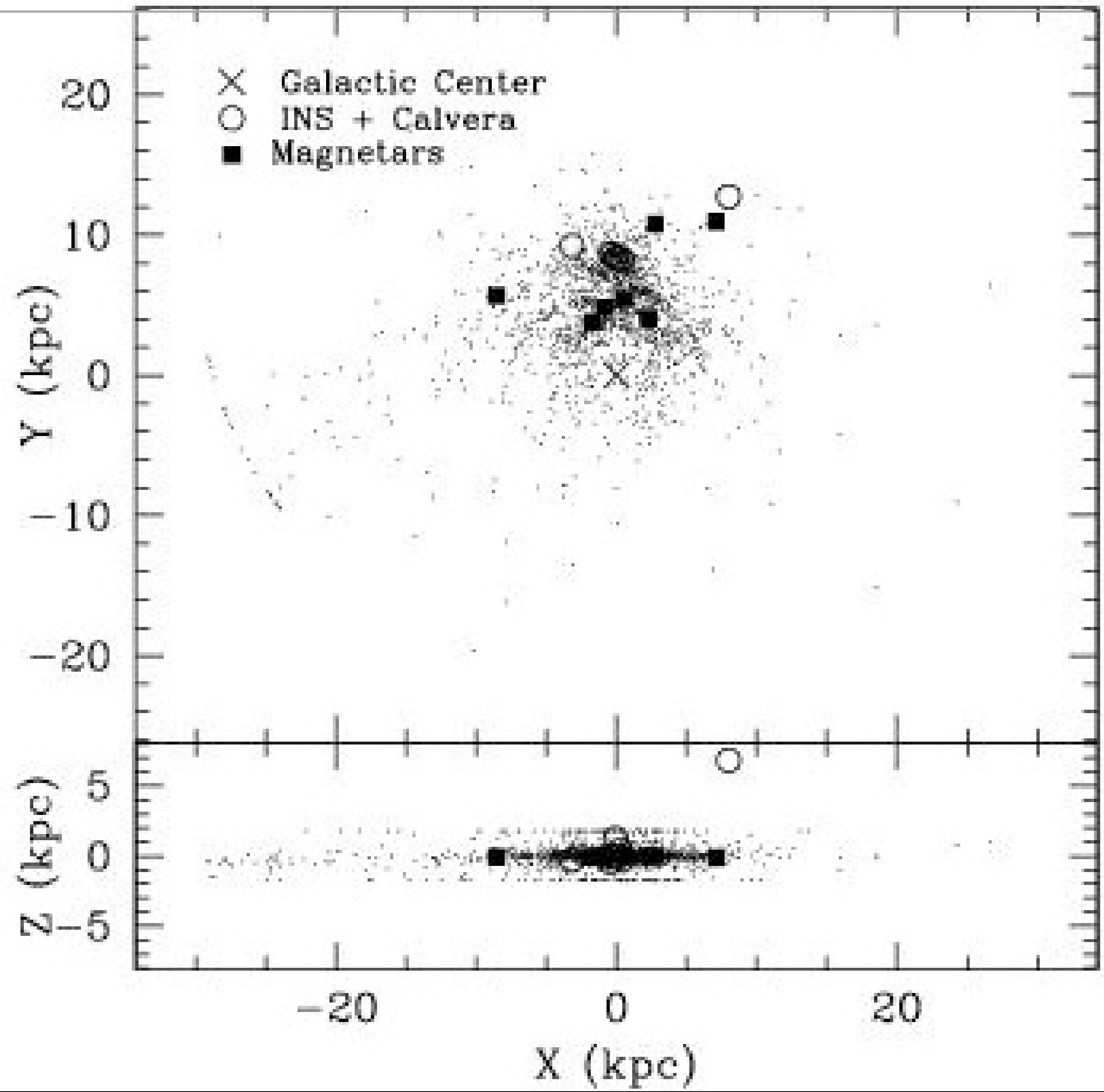
| Source | $kT_{\rm eff}$ (eV) | $F_X$ | (l,b) (deg,deg) | $X$ (kpc) | $Y$ (kpc) | $Z$ (kpc) | d (kpc) | $R_c$ (kpc) | Refs. |
|---|---|---|---|---|---|---|---|---|---|
| 1RXS J0420.0−5022 | 45 | 5 | 258, -44 | -0.36 | 8.58 | -0.35 | 0.51 | 8.59 | 1 |
| RXJ0720.4−3125 | 90 | 100 | 244, -8 | -0.45 | 8.72 | -0.07 | 0.50 | 8.73 | 2 |
| RXJ0806.4−4123 | 95 | 2.8 | 257, -5 | -3.29 | 9.26 | -0.30 | 3.39 | 9.83 | 3 |
| 1RXS J130848.6+212708 | 117 | 45 | 339, 83 | -0.06 | 8.35 | 1.29 | 1.30 | 8.45 | 4 |
| Calvera | 220 | 7.6 | 118, 37 | 7.82 | 12.66 | 6.68 | 11.10 | 16.31 | present |
| 1RXS J1605.3+3249 | 91 | 88 | 53, 48 | 0.30 | 8.27 | 0.42 | 0.56 | 8.29 | 5 |
| 1RXS J185635.1−375433 | 63.5 | 210 | 359, -17 | 0.00 | 8.34 | -0.05 | 0.167 | 8.34 | 6 |
| 1RXS J214303.7+065419 | 91 | 87 | 63, -33 | 0.42 | 8.29 | -0.31 | 0.56 | 8.30 | 7 |

Note. — Galactic positions of the seven INSs, plus Calvera, under the assumption all have the same $R_{\rm bb}$ as 1RXS J185635.1−375433 at a distance of 167 pc (see text). Reading across the columns, we give the source name, the measured effective temperature, the X-ray flux in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (0.1 − 2.4 keV); the galactic longitude and latitude (l,b); the resulting galactic three dimensional coordinates $X$, $Y$, and $Z$, where (0,0,0) is Galactic Center, and (0,8.5,0) is the Sun's location (Taylor & Cordes 1993); the source's distance from the Sun $d$; and galacto-centric distance $R_c$, with the relevant references. These positions are plotted in Fig. 4.

References. — 1, Haberl et al. (2004); 2, Haberl et al. (2006); 3, Haberl et al. (2004); 4, Schwope et al. (1999); 5, Motch et al. (1999); 6, Burwitz et al. (2003); Kaplan et al. (2007); 7, Zampieri et al. (2001)

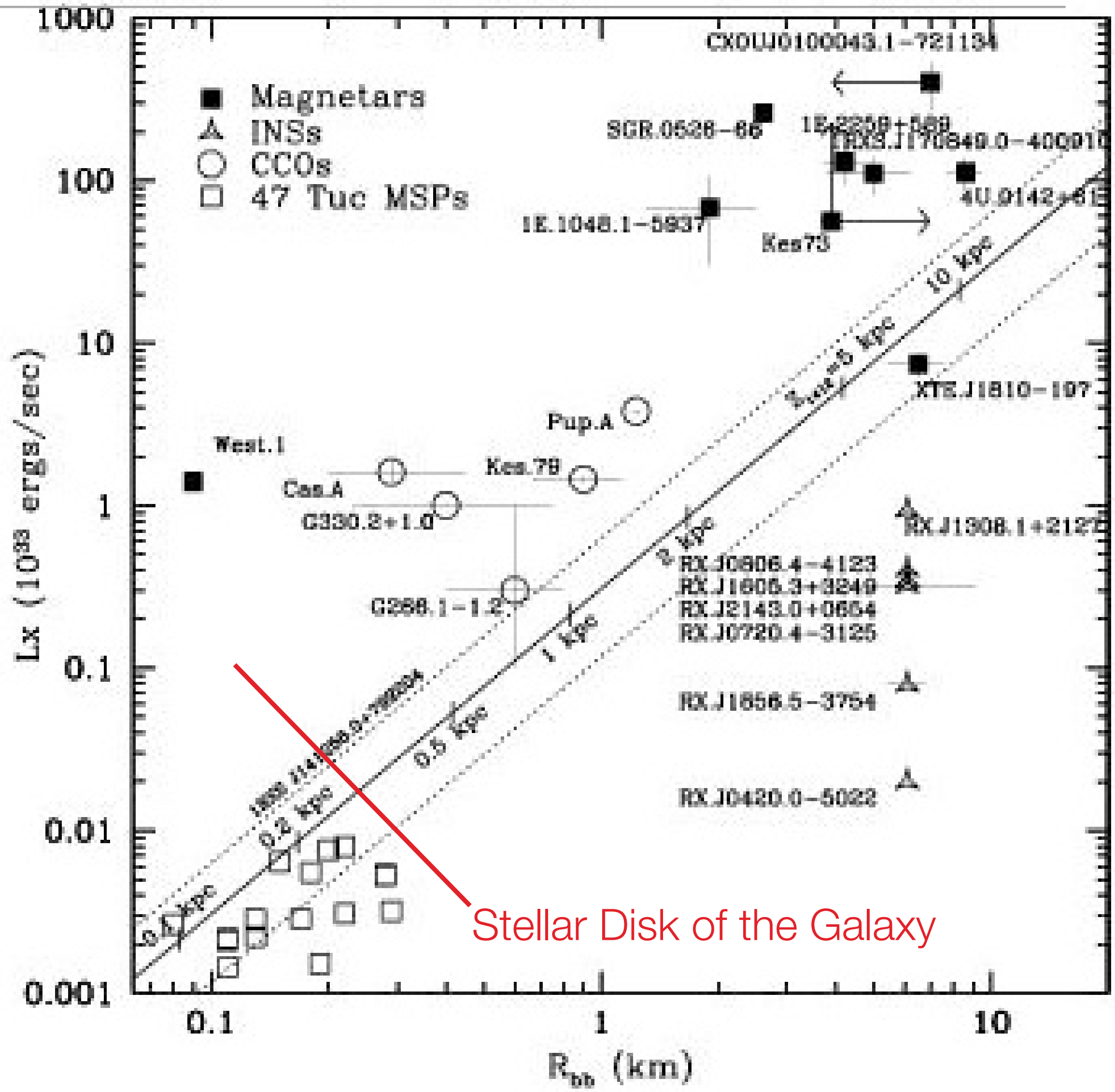
# Galactic Distribution of X-ray “Dim” Isolated Neutron Stars, if Calvera is like them.

- Z=6.7 kpc! (d=11 kpc)
- This requires a spatial velocity of >6700 km s-1.
- Or, it requires a cooling time >19 Myr (and kT remains 220 eV -- still higher than any known INS.



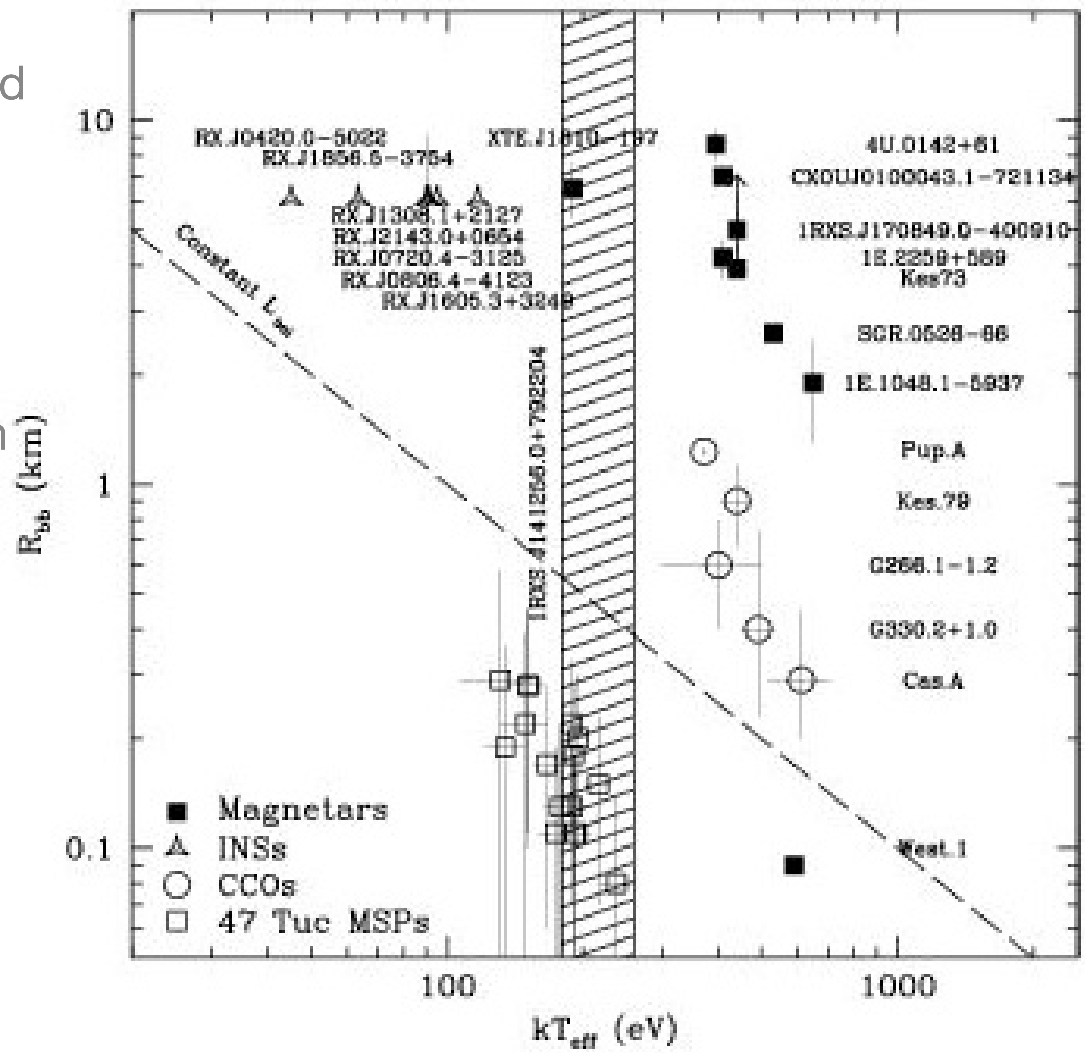
# R_bb vs. Lx

- R_bb is a function of distance (which is unknown).
- If R_bb is comparable to RX J1856, d=11 kpc, z=6.7 kpc.
- If L_X is comparable to magnetars (1e35 ergs/sec), d=110 kpc!



# kTeff vs. R_bb

- kTeff is lower than CCOs and magnetars.
- kTeff is greater than INSs
- But, comparable to MSPs in 47 Tuc.
- Comments on kTeff vs. Rbb for CCOs and Magnetars.



# Calvera: Observational Conclusions

- X-ray properties of Calvera are seriously challenging to explain, if the object is an INS (d=11 kpc; Z=6.7 kpc, requires a very high spatial velocity, or very long cooling time).

- X-ray properties are even more challenging to standard-candle magnetars (d=114 kpc), requiring even higher spatial velocity or longer cooling time.

- Could be a Compact Central Object, but without a supernova remnant? So what is a CCO? Simply a Compact object of arbitrary size?

- Object is *most* consistent with being a nearby (150-560 pc) radio pulsar. If it is an MSP, it is third X-ray brightest MSp in the sky, and only the third Northern MSP at <560 pc -- an interesting X-ray target, useful for a radio pulsar timing array, and LIGO.

- If the object is *not* a radio pulsar, then it is highly uncertain what type of compact object this is.