Chandra view of the Ultra-Luminous X-ray Source N10 in the Cartwheel galaxy

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Outline

• Why the Cartwheel?
• The Chandra observations of N10
• Derive the properties of some spectral ULX models for the source N10
• Models: accretion disc (several flavours), supernova
• **D = 122 Mpc (quite far!)**

• The Cartwheel owes its odd shape a major collision (with the galaxy G3) happened ~100 Myr ago (Higdon et al., 1986, Mapelli et al., 2008): strong burst of star formation (SFR=15-25 M☉/yr: Wolter & Trinchieri, 2004)

• Bright X-ray emission from the diffuse gas (6 x 10^{40} erg/s, Wolter & Tricheri, 2004)

• Extremely metal poor environment (Fosbury & Hawarden, 1977)

• 10-15 ULXs in the ring: Lx≈10^{39}-10^{41} erg/s, many of them variable
X-ray Compact Sources in the Cartwheel Galaxy
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X-ray sources

Optical
## Chandra observation log of N10

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### Diagram: Flux 0.5–10.0 keV \(10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}\)

- The diagram shows the flux over the years from 1995 to 2005.
- The data points represent the observations with error bars indicating the variability.
- The trend indicates a gradual increase in flux over time.
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$\text{L}_x \sim 10^{40}-10^{41}$ erg/s

Fading source!
Spectral modelling with Chandra

- The good news: little gas/instrumental bkg contamination (tiny PSF)
- The bad news: few photons: all the spectral models return similar $\chi^2$ (or C-stat). It is impossible to discriminate them on purely statistical grounds: we have to resort to the self-consistency of the interpretation
N10 as an Accreting Black Hole
N10 as an Accreting Black Hole

- Standard multicolour disc (MCD) around a Schwarzschild BH
- Kerr disc (around a fast-spinning BH)
- Slim disc (super-Eddington, radiatively inefficient)
MCD discs

- Locally radiate as black bodies
- Appropriate for accretion regimes below Eddington
- Temperature profile $T(R) \sim R^{-3/4}$
- Opacity due to electron scattering
- Compton hardening: parameter $f = T_{\text{col}} / T_{\text{eff}} \sim 1.7 - 2$ for accretion rates $0.1 - 1 \ L_{\text{Edd}}$ (Shimura & Takahara 1995); $f \sim 2.3 - 6.5$ for strongly super-Eddington regimes (Kawaguchi 2003)
Estimating the BH mass

\[ R_D = \xi \left( \frac{L_D}{4 \pi \sigma_{SB}} \right)^{1/2} \left( \frac{T_{\text{in}}}{f} \right)^{-2} \]

- Hypothesis: the disc extends all the way down to the last stable orbit: \( R_D = R_{\text{LSO}} \)
- \( T_{\text{in}} \) from the shape of the spectrum
- \( L_D \) from the count rate
- \( R_D \): normalisation

\[ R_D = \frac{6 G M_\bullet}{c^2} \]
Simple models (MCD only) yield relatively high temperatures (1.33, 1.21 and 0.89 keV)

\( M_{\text{BH}} \sim 61_{-12}^{+18} (f/2.0)^2 \, M_\odot \), (face-on disc)

\( L \lesssim 5 \, L_{\text{Edd}} \), and the hardening parameter \( f=2 \) is consistent with such a (relatively low) accretion regime
• Adding a hard spectral component (e.g. a Compton corona) lowers the best-fitting temperatures (0.53, 0.36 and 0.09 keV), and raises $M_{BH}$ to $\sim 140_{-42}^{+78} \times (f/1.7)^2 \, M_\odot$

• The hole accretes close to the Eddington limit (or $\sim 2 \times 10^{-6} \, M_\odot/yr$)

• $\tau \sim 1$
Slim discs

- Refinement of MCDs, appropriate for high (super-Eddington) mass accretion rates
- Disc heat content dragged inside the horizon before it can be radiated
- Radiative inefficiency $L \sim T_{in}^2$ (Watarai et al., 2001)
- $T(R) \sim R^{-1/2}$
Slim disc models: results

- BH mass consistent with anything above 80 M\odot
- Accretion rates 5 to 40 times the Eddington rate \( (=L_{\text{Edd}}/c^2) \)
- Caveat: we find: \( T \sim R^{-3/4} \), (diskpbb spectral model)
- Other ULXs successfully modelled with slim discs give the \( T(R) \) expected from slim discs (e.g. Watarai et al., 2000; Ohsuga et al. 2003)
The (extreme) Kerr disc

- Same conclusions as before, MBH is consistently around $90 \, M_\odot$ with no extra hard component
- Caveat: the hole’s mass is inferred from the observed luminosity, and it depends on the inclination angle. An almost edge-on disc yields $M_{BH} \approx 10^3 \, M_\odot$
Summary of the accretion model(s)

- Slim discs models not fully supported (T-R)
- Self-consistent accretion models return a \(~100 \text{ M}\odot\) black hole accreting close to \(L_{\text{Edd}}\) or \(~2 \times 10^{-6} \text{ M}\odot/\text{yr}\)
- Higher BH mass are possible, if the disc is almost edge-on
A 100 M☉ BH is a borderline case of the end product of the evolution of a massive star (HMXB)

The mass accretion rate is consistent with a disc accretion from a massive donor on a thermal time scale

In a metal-poor environment (Cartwheel), massive stars are more likely to form (Yungelson et al., 2008, Ohkubo et al, 2008)

Stars > 40 M☉ do not explode as SNe but directly collapse into BHs (Fryer, 1999; Fryer & Kalogera, 2001), retaining their initial mass
N10 as a Supernova
N10 as a Supernova

- SNe suggested as an explanation for some ULXs, as alternatives to accreting BHs
- ~25% of the ULXs are estimated to be young SNe (Swartz et al., 2004)
- Few X-ray SNe known (15, as of 2003; review by Immler and Lewin 2003)
- $L_x = 10^{37} - 10^{41}$ erg/s
- Powered by the interaction btw the ejecta and the circumstellar medium
SN interaction with the CSM

Chevalier and Fransson (2001)
X-rays from a SN Reverse Shock?

- Well modelled with a thermal model (APEC/NEI) with $C/ndf=95.9/100$
- $T=5.1^{-1.6}_{+3.1}$ keV, and metallicity $<0.2$ solar; OK with the low metallicity measured by Fosbury & Hawarden, 1977
- Normalisation consistent with size ($\sim 10^{15}$ cm) and density ($10^{-15}-10^{-16}$ g cm$^{-3}$) of a young SN
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CONCLUSION: the data are consistent with a SN (IIn)
Summary

• N10 is the brightest ULX in the Cartwheel, $L_X \sim 10^{40}-10^{41}$ erg/s

• Accretion models: N10 is a BH of $\sim 100 \, M_\odot$ accreting close to the Eddington limit $\sim 2 \times 10^{-6} \, M_\odot/yr$

• Higher masses ($\sim 1000 \, M_\odot$) are still possible, if the disc is seen almost edge-on

• Alternatively, N10 may still be a young, fading SN, most likely of type IIn

• .... so we need more Chandra time to discriminate the models