The Black Hole in NGC 1313 X-2

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Outline

• A bit of history
• Revisiting X-ray and optical observations of NGC 1313 X-2
• Evolution of the binary system
• NGC 1313 X-2 in context
• Conclusions and future perspectives
NGC 1313 and its ULXs

- Barred spiral galaxy (SBc) at ~4 Mpc
- SFR~1 Msun/yr (Ryder & Dopita 94)
- Z~0.1 Zsun (Pilyugin et al. 04)
- 2+1 ULXs, serendipitously discovered with *Einstein* IPC (Fabbiano & Trinchieri 87)
- One close to the nucleus, the other 2 at the outskirts

- X-2 included in the *EMSS* as MS 0317.7-6647
- Located ~6’ S to the nucleus
- **Galactic isolated NS or a binary containing a massive BH in NGC 1313** (Stocke et al. 95)
**X-ray observations**

**Einstein 1980** *(Fabbiano & Trinchieri 1987)*

**ROSAT 1991-1998** *(Stocke et al. 95, Colbert et al. 95, Miller et al. 98, Schlegel et al. 00)*

**ASCA 1993-1995** *(Petre et al. 94, Makishima et al. 00)*

**Chandra and XMM-Newton 2000-2006**

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High statistics XMM spectra: physical disc+corona models → thick coronae, no BH mass

(e.g. Stobbart et al. 06; Gladstone et al. 09)

Two spectral states (Fabio Pintore’s talk):

1. $L_x = 2e^{39-1e40} \text{ erg/s}$
   $T_c \sim 1.5 \text{ keV}, \tau \sim 10$,
   $T_{in} \sim 250 \text{ eV}$

2. $L_x = 2e^{39} \text{ erg/s}$
   $T_c \sim 3 \text{ keV}, \tau \sim 5$
A bit of history: optical counterpart

Optical observations

• Object C (C1+C2) identified thanks to accurate Chandra astrometry, after registering with SN 1978K (Zampieri et al. 04; Mucciarelli et al. 05,07) or a background AGN (Liu et al. 07): B=23.67±0.10, V=23.70±0.08

• VLT+FORS1 spectrum of C1: evidence of a broad 4686 He II line produced by X-ray irradiation: Mbh<50 Msun (Pakull et al. 06; Grise` et al. 08)

• HST+WFPC2 monitoring: tentative orbital period P=6.12±0.16 days (Liu et al. 09)
A bit of history: optical environment

- Extended (~400 pc) bubble nebula detected in Halpha (Pakull & Mirioni 02; Pakull et al. 2006)
- SN explosion(s) or wind/jet activity:
  * Energy~1e51-1e53 erg
  * Power~1e38-1e40 erg/s
  * Lifetime~1 Myrs
- Parent stellar association: two groups of (a few) young stars, spread out over ≈ 200 pc (Pakull et al. 2006; Liu et al. 07)
- Age of largest association 20+/−5 Myrs (Grise et al. 08,09)
Revisiting VLT+HST photometry

11 VLT+FORS1 epochs (October 2007 - March 2008; Grise` et al. 2009) plus 20 HST+WFPC2 epochs (May-June 2008; Liu et al. 2009) \(\rightarrow\) Domenico Impiombato's poster #1

- Differential photometry in the B band
- Short term variability:
  - VLT~0.04 mag
  - HST~0.1 mag
- Part likely due to X-ray irradiation
- Part apparently sinusoidal
- Best fitting sinusoid:
  - \(P=6+/-0.1\) days
  - \(A=0.09+/-0.01\)
6 (or 12) days optical period?

- Significance: ~2-3 sigma (from Lomb-Scargle periodogram and epoch folding)
- VLT data alone do not show periodicity, but are consistent with it
- HST V band data: no statistically significant modulation \( \rightarrow \) <0.06 mag
- If interpreted as orbital period: 6 or 12 days, depending on the extent of ellipsoidal modulations
Metallicity of the bubble nebula

Metallicity of HII regions: $Z = 0.2 \, Z_{\text{sun}}$ (Ryder 1993) and $Z = 0.5 \, Z_{\text{sun}}$ (Hadfield & Crowther 2007; Walsh & Roy 1997)

- Abundance analysis from nebular lines (only photoionization accounted for) → Emanuele Ripamonti’s talk
- **Cloudy** (Ferland 1996):
  * star ($T_{\text{eff}}=25000$-$45000$ K)+disc
  * standard dust/gas
  * $n=1$-$100$ cm$^{-3}$
  * $N_{h}=1\times10^{19}$-$2\times10^{21}$ cm$^{-2}$
  * $N/H=1/3$ solar (e.g. Pilyugin et al. 04)

Z=0.15-0.5 Zsun
Evolution of the binary system

**ULX binary model** (Patruno & Zampieri 08, 10)

- Eggleton code, non-conservative evolution with wind loss and gravitational wave emission
  
  $Z=0.2-0.5\ Z_{\odot}$: minimal effect on tracks ($Z=0.01$)

- UV/optical luminosity computed summing to the donor emission the contribution of the accretion disc, and including the effects of X-ray reprocessing

- Geometrically thin optically thick accretion disc ($e=0.1$)

  If $\dot{M} > \dot{M}_{\text{Edd}}$, we impose $\dot{M} = \dot{M}_{\text{Edd}} \rightarrow$ excess mass expelled from the system

- Depending on initial separation, RLOF may start
  
  * during MS: **case AB**
  
  * after MS: **case B** $\rightarrow$ contact phase too short with respect to the characteristic age of the nebula ($\sim1\\text{Myrs}$)
Evolution of the binary: 20 Msun BH

- 10-20 Msun donor consistent with C1 during H-shell burning
- Consistency with parent cluster age (15-25 Myrs) : $M_{\text{donor}}=12-15$ Msun
  Mass transfer rate above Eddington $\rightarrow$ excess mass expelled

- First contact phase during MS sufficiently long to inject the required energy in the nebula
Evolution of the binary: 70 Msun BH

- 12-20 Msun donors consistent with C1 during terminal age MS
- Consistency with parent cluster age (15-25 Myrs) and average mass transfer rate (1e-6 Msun/yr) \( \rightarrow M_{\text{donor}} = 12-15 \) Msun

- Similar result for BHs between 50 and 100 Msun
Constraint from orbital period

- $M_{bh} = 50-100 \text{ Msun} + \text{MS donor (P=1-6 days)}$
  - $M_{donor} = 12-15 \text{ Msun}$ crosses C1 with $P \sim 5-6 \text{ days}$
- $M_{bh} = 20 \text{ Msun} + \text{H-shell burning donor (P=4-20 days)}$
  - $M_{donor} = 12-15 \text{ Msun}$ crosses C1 with $8 < P < 10 \text{ days}$
  - If $P \sim 12 \text{ days}$, $M_{donor} \sim 20 \text{ Msun}$ in order to cross C1
  - Beaming/no-irradiation: $M_{donor} \sim 15 \text{ Msun}$ crosses C1 with $P \sim 15 \text{ days}$

\[\text{Mbh}=70 \text{ Msun}\]
\[\text{Mbh}=20 \text{ Msun}\]
If $P$ is different from 6 or 12 d?

- $P=5-6$ days
  
  \[ \text{Mbh} = 50-100 \text{ Msun} + \text{MS} 12-15 \text{ Msun} \]

- $P>8$ days
  
  \[ \text{Mbh} = 20 \text{ Msun} + \text{H-shell burning} 12-15 \text{ Msun} \]

- $P<4$ days
  
  **SuperEddington luminosity**

- For Mbh between 20 and 50 Msun there may also be agreement with observations for different values of $P$

- Modelling the light curve may give additional clues
  
  * X-ray irradiation (0.05–0.15 mag; unless the source is beamed)+ellipsoidal modulations (0.1–0.2 mag)+disc emission
  * Superposition gives an asymmetric modulation
NGC 1313 X-2 in context

50-100 Msun BH + 12-15 Msun MS donor

- Such a system fits well within a low-metallicity formation scenario (Mapelli et al. 2009, 2010; Zampieri & Roberts 2009) → Michela Mapelli’s talk
  * If an envelope more massive than ∼30-40Msun is retained at the time of explosion, a low metallicity (Z~0.1Zsun) star may collapse directly to form a BH (Heger et al. 2003; Belczynski et al. 2009)
  * The supernova shock wave loses too much energy in trying to unbind the envelope until it stalls and most of the star collapses into a BH of mass comparable to its final mass (>30-40 Msun; Fryer 1999; Zampieri 02)

- Only modest beaming (bf ~ 0.5) or slight violations of the Eddington limit (a factor of a few) would be needed for bright (> 1e40 erg/s) ULXs
- Essentially isotropic irradiation of the X-ray photoionised nebulae explained
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Essentially isotropic irradiation of the X-ray photoionised nebulae explained NGC 1313 X-2 in context.
Conclusions and future perspectives

NGC 1313 X-2

- Revisted X-ray and optical observations
- Optical modulation (~2-3 sigma)?
  If confirmed, orbital period $P=6$ days or $P=12$ days
- Modelling the binary evolution subject to all the X-ray and optical observational constraints provides different outcomes:
  \[
  P=5-6 \text{ days} \quad \rightarrow \quad \text{Mbh} = 50-100 \text{ Msun} + \text{ MS 12-15 Msun}
  \]
  \[
  8<P<10 \text{ days} \quad \rightarrow \quad \text{Mbh} = 20 \text{ Msun} + \text{ H-shell burning 12-15 Msun}
  \]
  \[
  P>10 \text{ days} \quad \rightarrow \quad 20-50 \text{ Msun and/or no-irradiation}
  \]
  \[
  P<4 \text{ days} \quad \rightarrow \quad \text{superEddington luminosity in any case}
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- More robust assessment of $P$ needed!