Ultraluminous X-ray Sources forming in low metallicity natal environments

Luca Zampieri

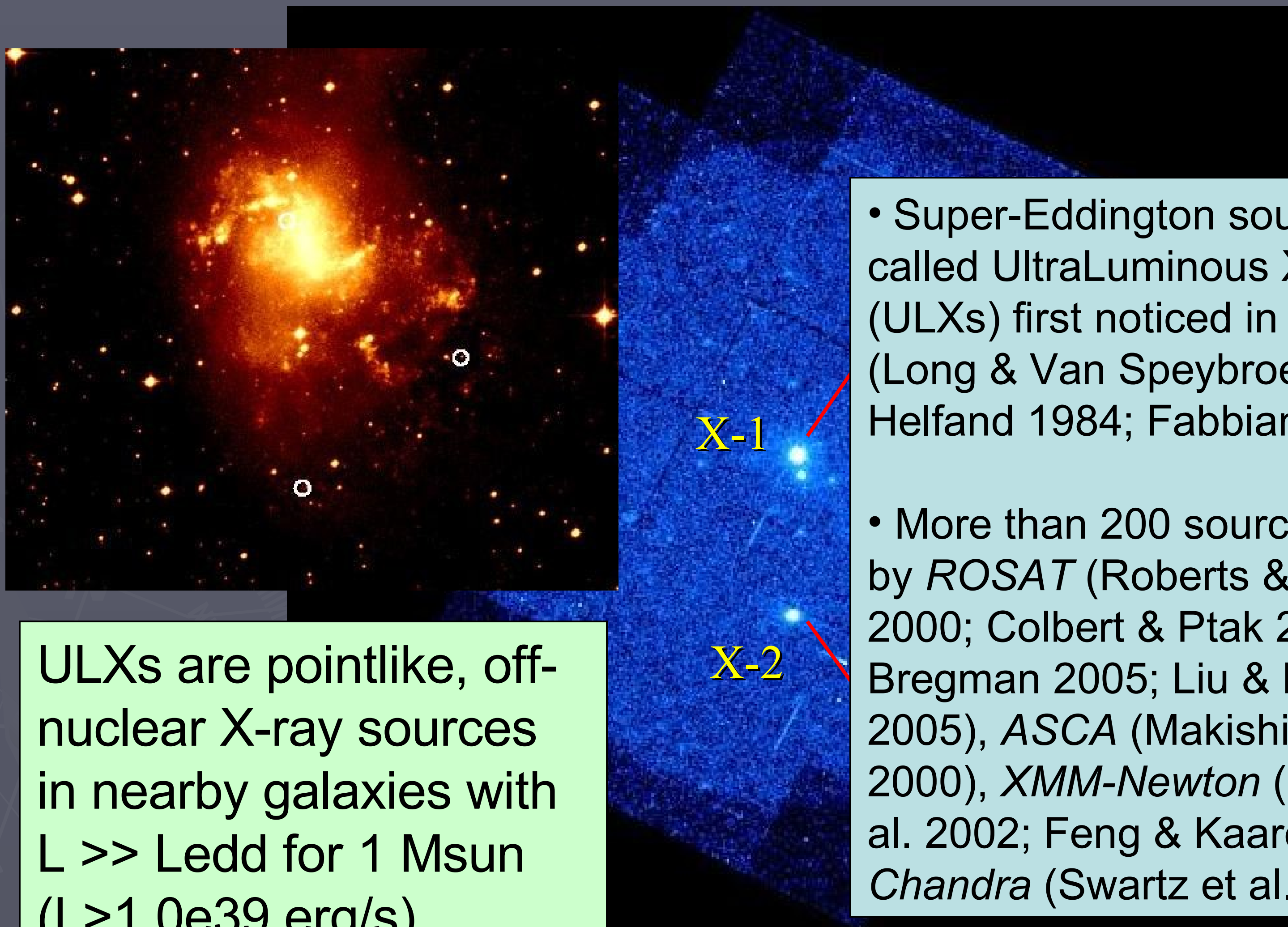
INAF-Astronomical Observatory of Padova

M. Colpi, M. Mapelli, A. Patruno, T. P. Roberts

Outline

- Intermediate or stellar mass black holes interpretation
- ULXs forming in low metallicity natal environments?
  → 30-80 Msun BHs
- Massive BHs in the Cartwheel galaxy
- Independent evidence from NGC 1313 X-2?
- Conclusions

Ultraluminous X-ray Sources



- Super-Eddington sources, later called UltraLuminous X-ray sources (ULXs) first noticed in *Einstein* data (Long & Van Speybroeck 1983; Helfand 1984; Fabbiano 1989)

- More than 200 sources observed by *ROSAT* (Roberts & Warwick 2000; Colbert & Ptak 2002; Liu & Bregman 2005; Liu & Mirabel 2005), *ASCA* (Makishima et al. 2000), *XMM-Newton* (Foschini et al. 2002; Feng & Kaaret 2005), *Chandra* (Swartz et al. 2005)

ULXs are pointlike, off-nuclear X-ray sources in nearby galaxies with L >> Ledd for 1 Msun (L>1.0e39 erg/s)

What are Ultraluminous X-ray Sources

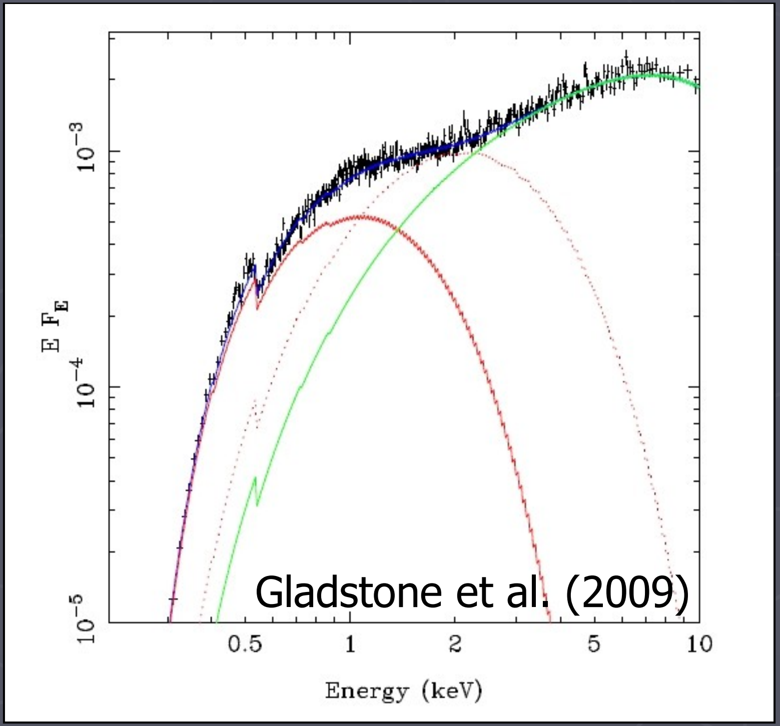
ULXs are <u>X-ray binaries with massive donors</u>

- X-ray spectra: Similar to BHC spectra
- High luminosity end of the XLF of XRBs
- Embedded in young stellar environ.
- Detection of stellar optical counterparts
- QPO in the PDS
- Modulation in the X-ray and optical light curve
- X-ray flux variability, Lx-spectral variability

Intermediate or stellar mass BHs?

ULX models differ in the assumptions on the physical state of the disc

- Accretion disk in a standard regime
  * Isotropic X-ray emission → IMBHs (Colbert & Mushotzky 1999)
  * Early X-ray spectroscopy estimates based on MCD+PL fits → IMBHs
  * How big is the BH mass? **Mbh>100-1000 Msun** (e.g. Miller et al. 03)
  * Recently spectroscopic estimates of Mbh partly revised (e.g. Lorenzin & Zampieri 09; Hui & Krolik 08) or questionned (e.g. Goncalves & Soria 06; Stobbart et al. 06; Soria & Kuncic 2007)
  * Other, physical X-ray spectral models: disc+Comptonized, thick corona
    → T not good indicator of Mbh
    → From VHS to ultraluminous state
    See talk by Tim Roberts



Intermediate or stellar mass BHs?

- Accretion flow in a different regime. Isotropy and/or the Eddington limit may be circumvented → stellar mass BHs (**Mbh=10-20 Msun**; King et al. 01)

  * Slim disk (Ebisawa et al. 03)

  * Photon-bubble disks (Begelman 02, 06)

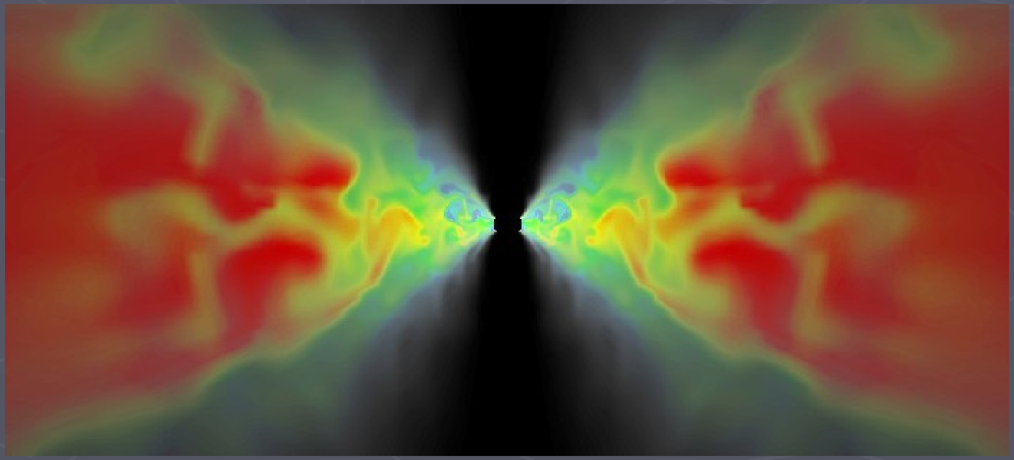
  * Radiatively efficient, two-phase super-Eddington discs (Socrates & Davis 06)

  * Thick disks with beaming (King 02)

  * Thick disks with beaming and super-Eddington L (Poutanen et al. 07; King 09)

$$L=[1+\ln(\dot{M}/\dot{M}_{Edd})]L_{Edd}$$

Consistent with disc+Comptonized, thick corona X-ray spectral models



Intermediate or stellar mass BHs?

- IMBHs

  Current observational evidence (in particular from X-ray spectra) indicates that BHs of several hundreds to thousands Msun are not required for the majority of ULXs; might be present in a handful of objects (such as the hyper-luminous ULXs with L~10^{41} erg/s)

- Stellar mass BHs

  Possible explanation up to ~10^{40} erg/s, but rather extreme conditions needed to account for ULXs above this (isotropic) L

- Different interpretation?

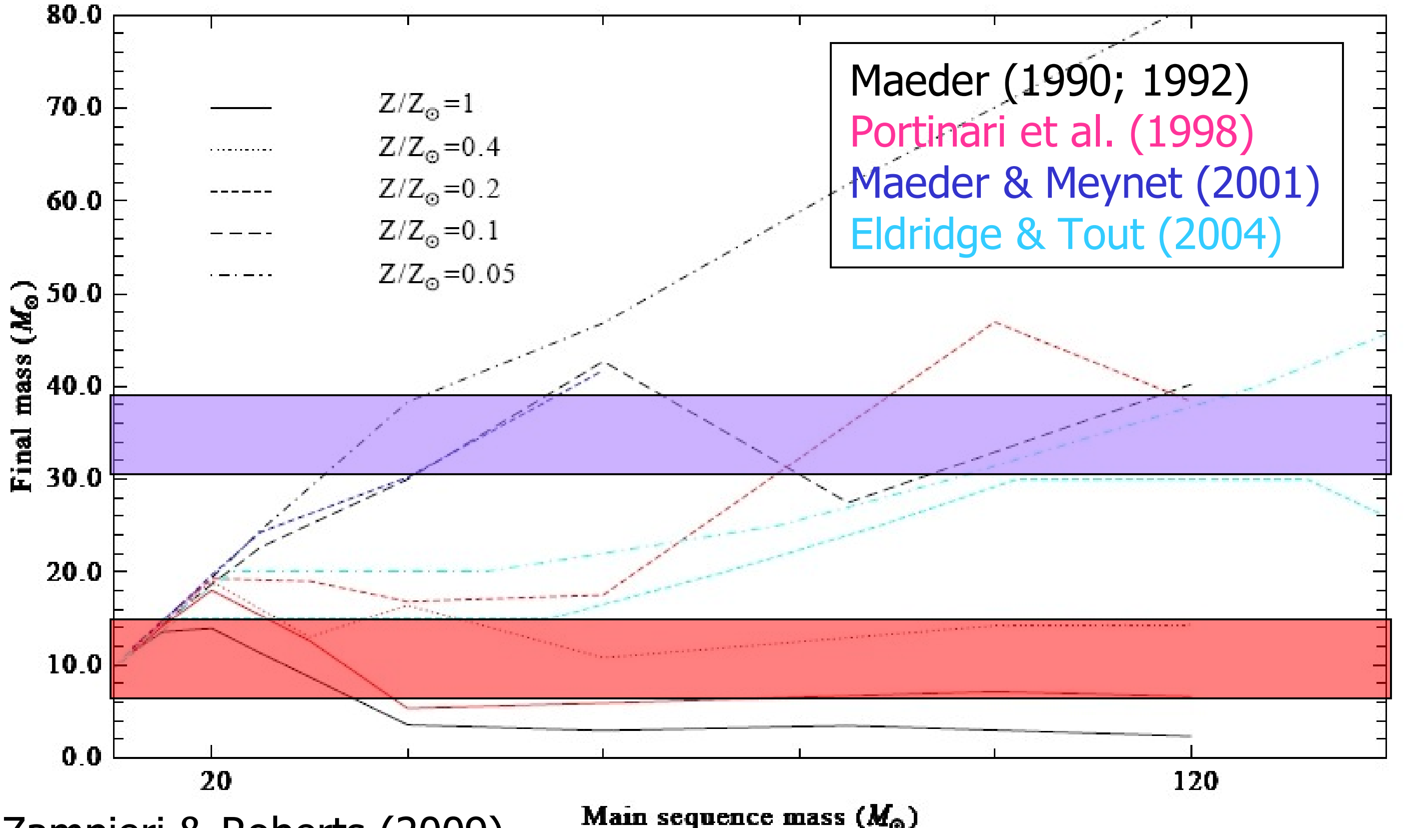
Low metallicity, massive stars

- Possible connection between ULXs and star formation in low metallicity environments (Pakull & Mirioni 02; Cropper et al. 04; Zampieri et al. 04)
- At sub-solar metallicities, line-driven winds become progressively less efficient and stars with masses above ~20Msun may retain rather massive envelopes at the time of explosion
- What is the final mass of the star?

  * According to the adopted mass loss history, it may differ up to a factor of ~2 (more for clumpy winds; e.g. Moffat & Carmelle 1994; Fullerton et al. 06)

  * Scaling law $\propto Z^{0.5}$ often adopted for the mass loss in hot stars (e.g. Kudritzki et al. 1989; Nugis & Lamers 2000)

Final mass of the star



Zampieri & Roberts (2009)

If the envelope is ~30-40Msun, the supernova shock wave loses too much energy in trying to unbind the envelope until it stalls and most of the star collapses (Fryer 1999; Zampieri 02)

Remnant mass

- A low metallicity (Z ~ 0.1-0.2 Zsun) star may retain a ~30-40Msun envelope and then collapse directly to form a BH (Heger et al. 2003; Belczynski et al. 2009)

  These may be the BHs hosted in some ULXs

- *If the core is not rapidly rotating, BH mass comparable to final mass:*

  Mbh>30-40 Msun

- Pros
  * Does not require new mechanism but is referable to stellar evolution
  * Continuum distribution of masses above 10-20Msun up to ~80 Msun consistent with the power-law slope of the XLF of the X-ray binary population of galaxies
  * Only modest beaming (bf ~ 0.5) or slight violations of the Eddington limit (a factor of a few) needed for bright (> 10^40 erg/s) ULXs
  * Consistent with isotropic irradiation of X-ray photoionised nebulae

Testing this interpretation

- *Metallicity of the environment*. Discrepancies between optical and X-ray data (e.g. Winter et al. 07): Optical spectrum of the nebula of Ho II X-1 → Z~0.1 Zsun (Pakull & Mirioni 02), but XMM-Newton RGS spectrum → Z~0.6 Zsun (Goad et al. 06)
- Specific ULX frequency decreases with increasing host galaxy mass indicating that smaller, lower metallicity systems have more ULXs per unit mass (Swartz et al. 2008)
- Dynamical mass measurement of the WR optical counterpart of IC 10 X-1 → 23-33 Msun (Prestwich et al. 2007; Silverman & Filippenko 08)

Massive BHs in the Cartwheel galaxy

- Metallicity of the Cartwheel: Z~0.05 Zsun (Fosbury & Hawarden 1977)
- Number of massive BHs (distribution of BHs ∝ IMF above 40 Msun; Mapelli et al. 09):

$$\mathrm{N_{BH}} = A \int_{40\,M_\odot}^{m_{\rm max}} m^{-\alpha}\, dm$$

A=SFR tburst/Mtot

$$\mathrm{M_{BH}} = A \int_{40\,M_\odot}^{m_{\rm max}} m^{-\alpha}\,(m\,b + c)\, dm$$

b=0.54, c=15.6Msun

SFR~20 Msun/yr (Mayya et al. 2005), tburst~10^7 yr

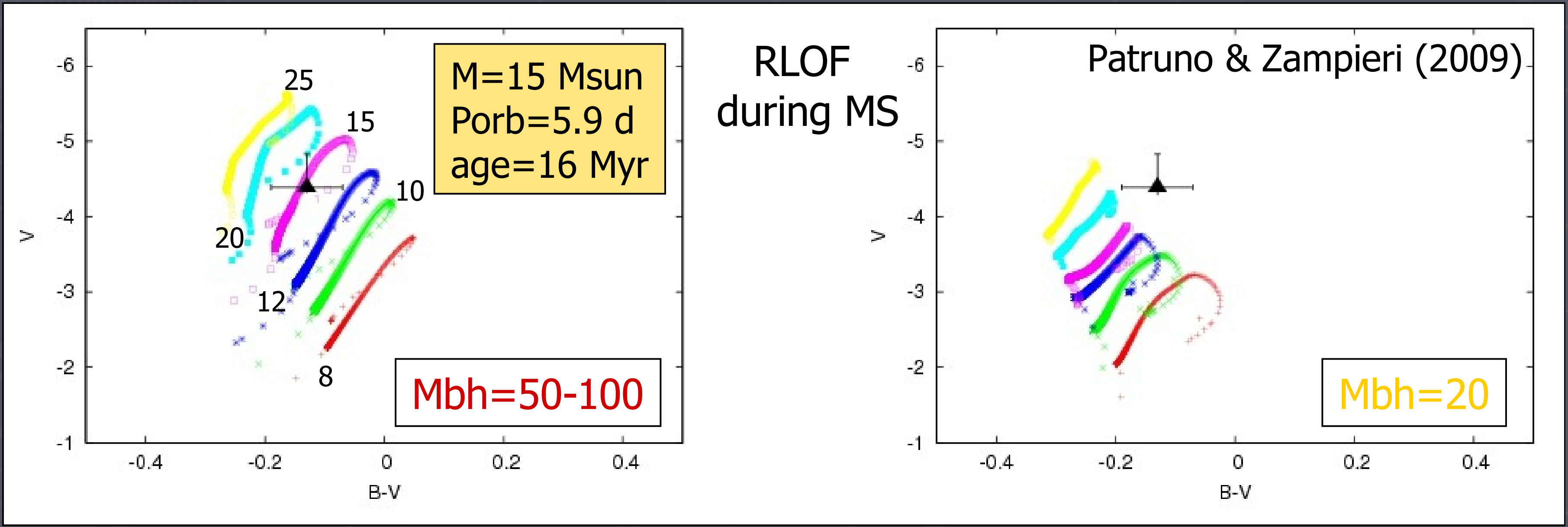
Nbh = 1.2×10^{5}-2.4×10^{5}

Mbh = 6.2×10^{6}-1.2×10^{7} Msun

- 3-6% of the total stellar mass in the ring
- *No difficulty with the fraction of star-forming mass ending up in BHs*
  (large mass in BH-forming clusters major problem for the IMBH interpretation; e.g. King 2004; Mapelli et al. 08)
- Reasonable production efficiency: Nulxs/Nbh~10^{-4}

NGC 1313 X-2: orbital period and Mbh

- Tentative identification of the orbital period in the HST optical lightcurve (3 cycles in the B band; Liu et al. 09): **P=6.12+/-0.16 d** → not confirmed by Grise' et al. (09)
- Optical data modelled using colour-magnitude diagram, orbital period, age of the parent cluster (20+/-5 Myr; Grise' et al. 08), age of the surrounding emission nebula (~1 Myr old; Pakull et al. 02)



Conclusions

- 100-1000 Msun BHs not required for the majority of ULXs; might be present in a hundful of objects
- Stellar mass (~10-20 Msun) BHs possible explanation for ULXs below ~10^{40} erg/s, but they need extreme conditions above this (isotropic) L
- Bright ULXs may contain BHs with masses above 30−40 Msun and up to 80−90 Msun, produced by low metallicity stars with initial mass above 40−50 Msun → *(very) massive BHs or (V)MBHs*

  * Formation referable to ordinary stellar evolution

  * Only modest violations of the Eddington limit

  * No difficulty with the fraction of star-forming mass in BHs

  * BH in NGC 1313 X-2 (Mbh=50-100 Msun)
- Future tests: → metallicity measurements (Ripamonti et al. 09)

  → surveys of ULX locations looking for a statistically meaningful relationship between position, average L and local Z (Mapelli et al. 09b)