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Metallicity measurements in the neighbourhood of ULXs

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Outline

1) Ultra-luminous X-ray sources (ULXs)

2) Metallicity & ULX formation

3) Metallicity measurements

4) Modelling the vicinity of ULXs

Ultra-luminous X-ray sources (ULXs)

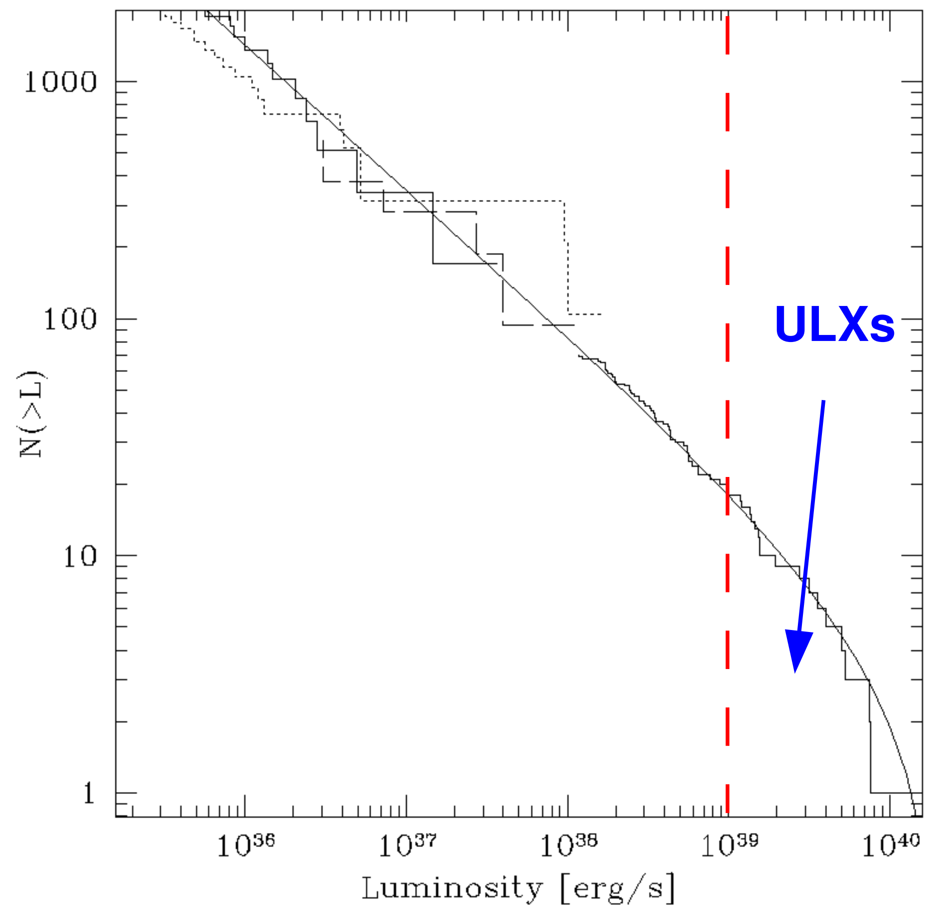
Non nuclear point-like X-ray sources with $L_X > 10^{39}$ erg/s

Non-nuclear → no AGN

$L_X > 10^{39}$ erg/s → over the Eddington limit for ~10 M_{sun} objects

Several hundreds sources;
most luminous have $L_X > 10^{41}$ erg/s

Grimm et al. 2003



More common in late type galaxies
(spirals, irregulars) than in early type galaxies (ellipticals, S0)

ULX models

Extension of High Mass X-Ray Binaries (HMXBs) on the luminosity function

→ same kind of objects (i.e. accreting BHs), only more massive?

- Stellar Black Holes → problems with stellar evolution theory
- Intermediate-mass BHs → do they really exist? Are they so common?

Ways around: normal stellar (~10 M_{sun}) BHs with

- non-isotropic emission → but "isotropic" nebulae have been detected
- super-Eddington accretion → how long? At what Eddington ratio?

Supernovae → definitely there; but can't explain sources where L_X goes up

Contamination (blended + background sources) → can be estimated

All these explanations have some merit; but none of them can explain the bulk of the ULX population

Role of metallicity – stellar BHs at $Z \sim Z_{sun}$

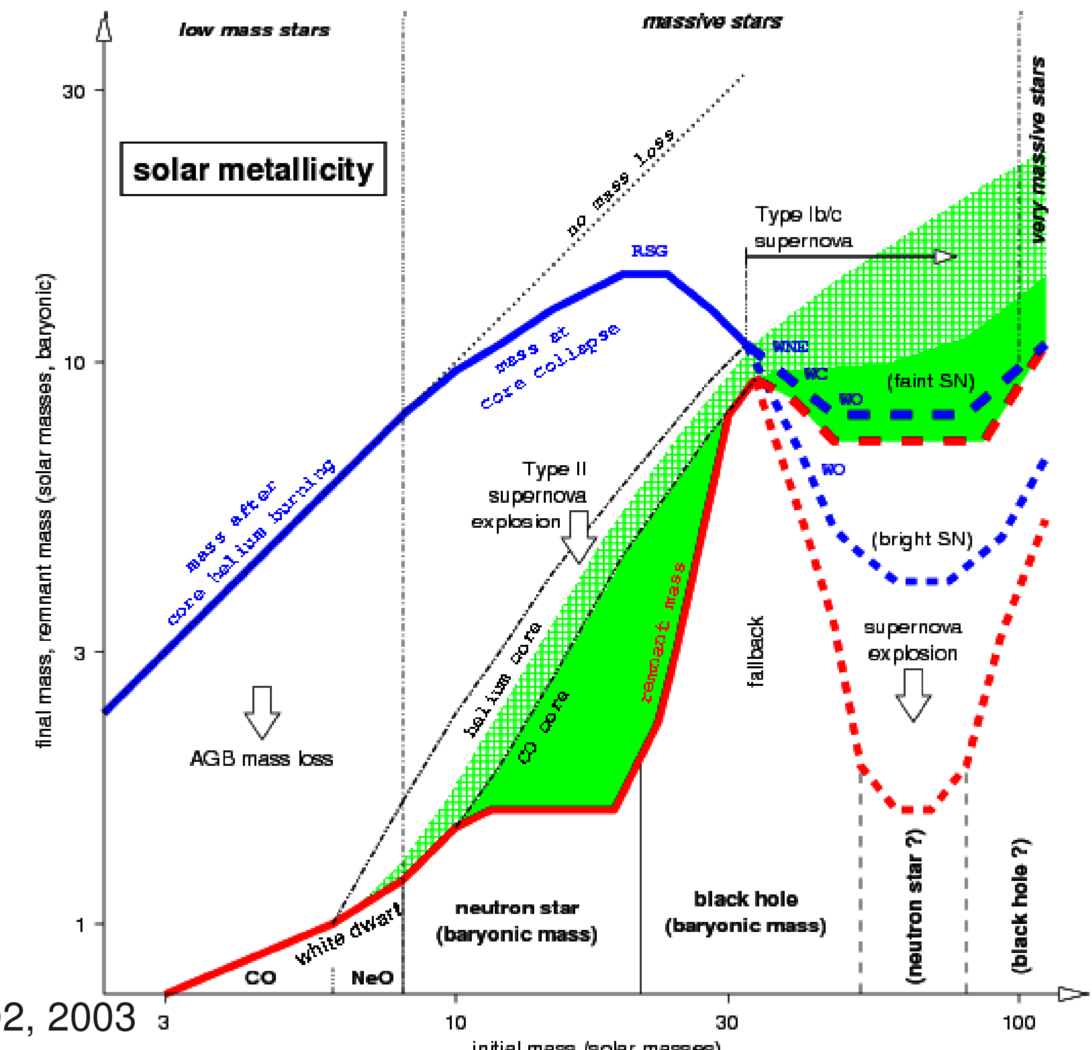
Extension of High Mass X-Ray Binaries (HMXBs) on the luminosity function

→ same kind of objects (i.e. accreting BHs), only more massive?

- Stellar Black Holes → problems with stellar evolution theory

Massive stars reduce their mass through:

1) Mass-loss in stellar winds
2) Ejection in supernova explosions



Heger et al. 2002, 2003

Role of metallicity – Massive stellar BHs at $Z<<Z_{sun}$

Extension of High Mass X-Ray Binaries (HMXBs) on the luminosity function

→ same kind of objects (i.e. accreting BHs), only more massive?

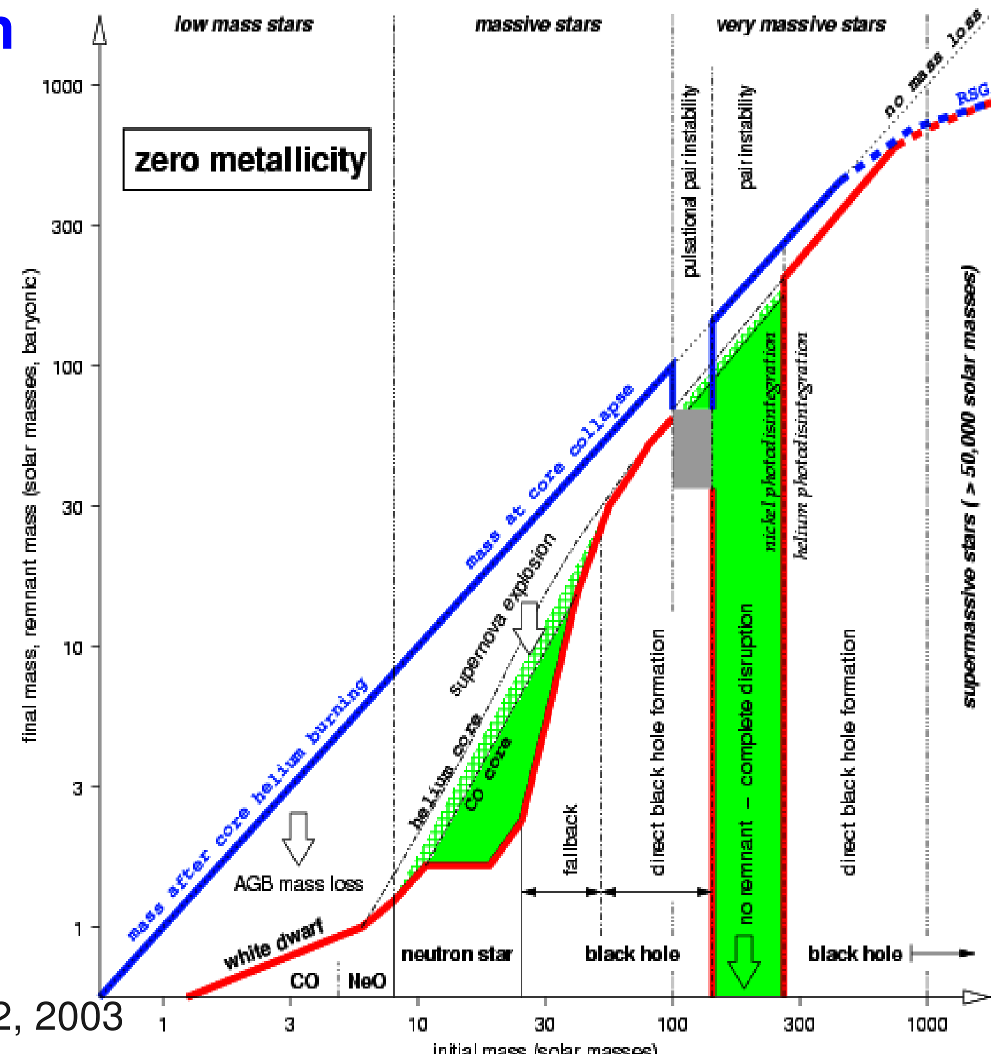
- Stellar Black Holes → problems with stellar evolution theory

Metallicity can affect this conclusion

stellar winds are stronger in high-Z stars
→ mass loss depends on Z

BHs can form through direct collapse
(no SN!) further reducing mass losses

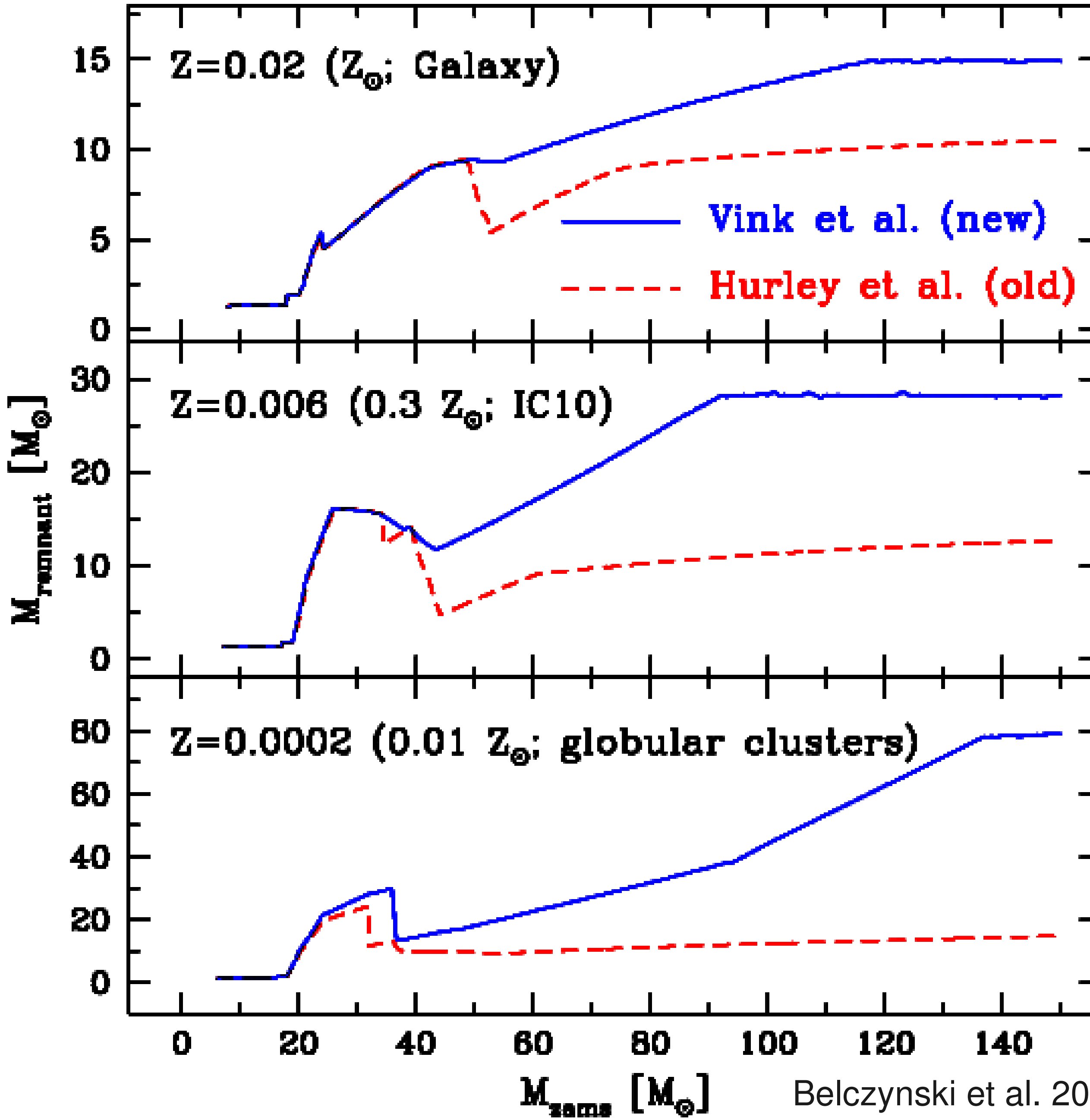
→ remnant mass depends on Z!



Heger et al. 2002, 2003

Role of metallicity – Massive stellar BHs at Z~0.01-0.3 Z_{sun}

30-80 M_{sun} BHs can form at Z <~ 0.3 Z_{sun}



Belczynski et al. 2010

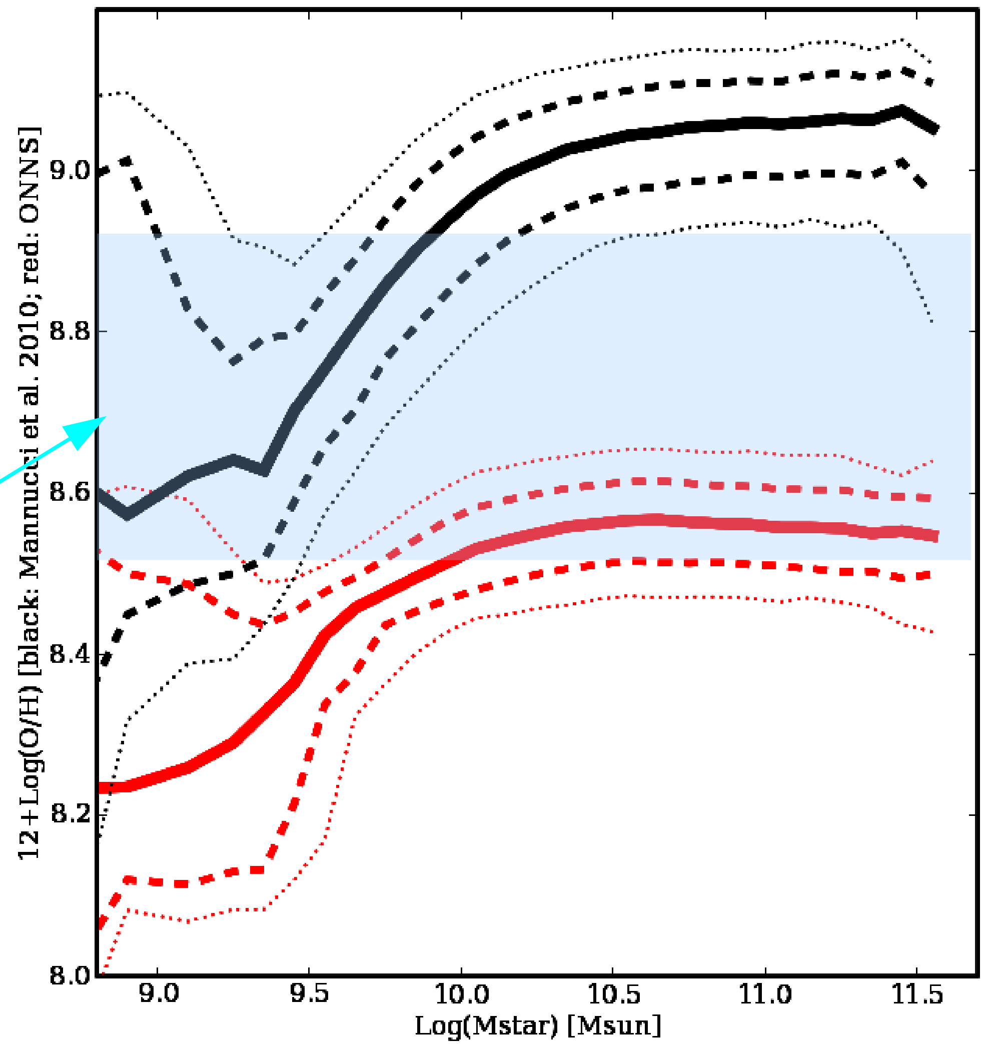
Metallicity measurements - general

Comparing different metallicity measurements is problematic

There are different methodologies e.g.:
- from emission lines in HII regions
- from absorption in stellar continua
  (single star or stellar population)
- from X-ray absorption edges

Differences in calibration even WITHIN the same methods

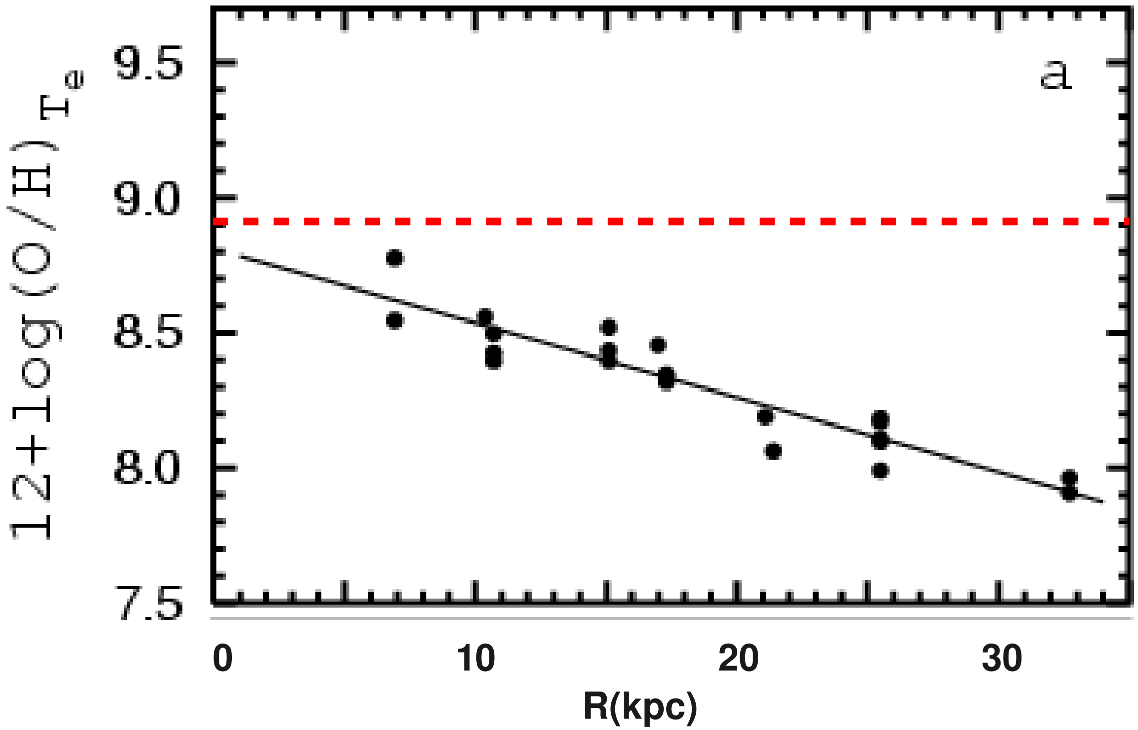
even the solar metallicity is uncertain by a factor ~ 2!



Metallicity measurements – HII regions

Most common measurements come from oxygen lines in HII regions
There are generally a large-scale gradient and a local scatter

Example: M 101 abundance profile (Pilyugin 2001)



The ionizing source is different: ULXs are different from stars
Can we use existing measurements?

NGC 1313 X-2: summary

Host galaxy properties

distance: 3.7 Mpc   metallicity: 2 HII regions with $Z=0.2\text{-}0.3\ Z_{sun}$ (PT05 cal.)

X-ray properties (at least 2 states)

luminosity(0.3-10 keV): ~2-30 $\times 10^{39}$ erg s^{-1}

spectrum: MCD + PL

kT: 0.13-0.25 keV Γ : 1.7-2.5

F_{MCD}/F_{PL} : 0.45-0.94

N_H: 2-4 x 10^{21} cm^{-2} ($N_{H,gal}$ = 4 x10^{20} cm^{-2})

Optical Counterpart

object C1, E(B-V)~0.1 (0.3?), M_V~-4.6±0.2,

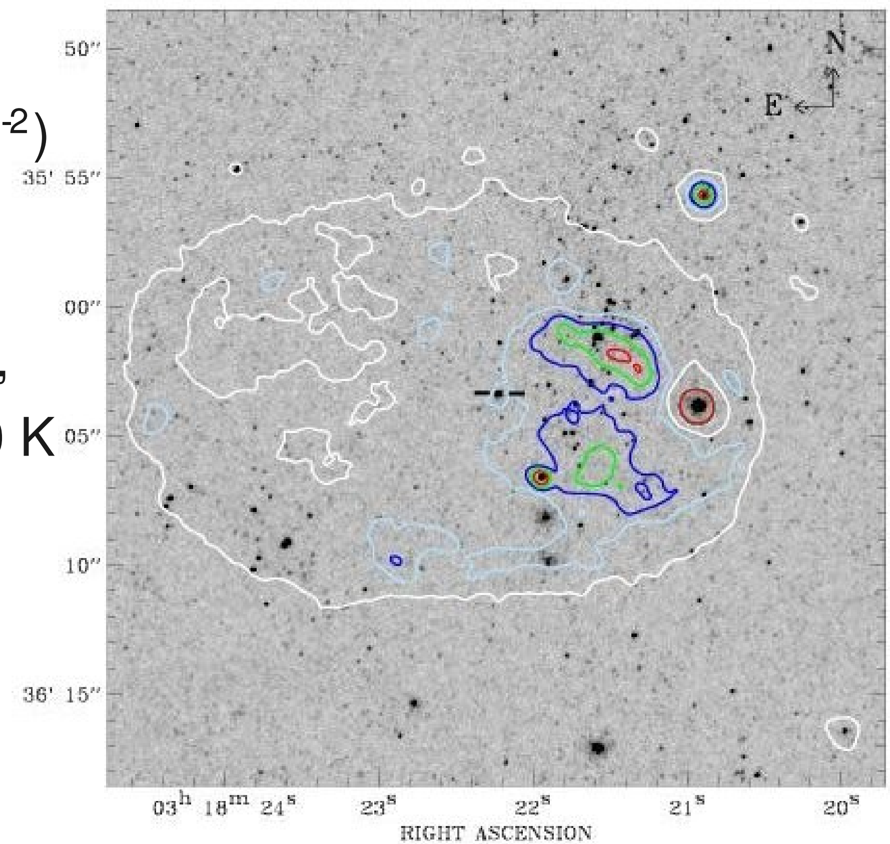
B-V~-0.13±0.06, 20000 K <~ T_{eff} <~ 30000 K

Optical nebula

~ 500x300 pc

blue population with age ~20 Myr

Grise' et al. 2008



Modelling

We use the photoionization code Cloudy (Ferland et al. 1998; www.nublado.org)

Model parameters

Incident spectrum: Companion star

T_{star} : 8 values, 26200 → 48000 K,

X-ray source

MCD(0.2 keV) + PL (Γ=2),

F_{MCD} =0.8F_{PL} , L(0.3-10 keV)=6x10^{39} erg s^{-1} ,

intrinsic N_H: 6 values, $N_{H,intr}$ =10^{19} → 2x10^{21} cm^{-2}

Nebula composition/density/geometry:

Overall metallicity: 13 values, Z = 1/40 Z_{sun} → 2 Z_{sun}

N/O ratio: 2 values, solar (Orion) or 1/3 solar

dust/metal ratio: 2 values, Orion or 1/10 Orion

density: 5 values: n = 1 → 100 cm^{-3}

Cloudy (raw) results - 1

grid of (8 T_{star}) x (6 $N_{H,intr}$) x (13 Z) x (2 N/O) x (2 dust/metal) x (5 n)
→ about 12000 models

sorted according to "score" (similar to a χ^2) given by comparison with observational constraints about line intensities and about the size of the nebula

Best score model

Z=0.2 Z_{sun} **N/O=1/3 solar** **dust/metal=1/10 solar,**

T_{star} =40000 K **$N_{H,intr}$ =10^{20} cm^{-2}** **n=1 cm^{-3}**

→ O2: 5.76(-0.20σ) O3: 2.60(+0.99σ) O1:0.87(-0.12σ)
N2: 0.59(-0.21σ) S2: 1.45(-1.19σ) R(HII)=405 pc

Agreement with "normal" calibration looks pretty good.....

Cloudy (raw) results - 2

grid of (8 T_{star}) x (6 $N_{H,intr}$) x (13 Z) x (2 N/O) x (2 dust/metal) x (5 n)
→ about 12000 models

sorted according to "score" (similar to a χ^2) given by comparison with observational constraints about line intensities and about the size of the nebula

Best score model

$Z=0.2\ Z_{sun}$ N/O=1/3 solar dust/metal=1/10 solar,

T_{star} =40000 K $N_{H,intr}$ $=10^{20}$ cm^{-2} n=1 cm^{-3}

→ O2: 5.76(-0.20σ) O3: 2.60(+0.99σ) O1:0.87(-0.12σ)
N2: 0.59(-0.21σ) S2: 1.45(-1.19σ) R(HII)=405 pc

NOT SO FAST: many acceptable models. Remarkably,

$Z=1.0\ Z_{sun}$ N/O=1/3 solar dust/metal=1/10 solar

T_{star} =35000 K $N_{H,intr}$ $=3\times10^{20}$ cm^{-2} n=1 cm^{-3}

→ O2: 5.77(-0.20σ) O3: 2.04(-0.27σ) O1:0.60(-0.71σ)
N2: 1.27(+2.39σ) S2: 1.90(-0.12σ) R(HII)=148 pc

Results: interpretation

Robust results

low N/O (<1/3 solar)

moderate $N_{H,intr}$ = 10^{20}-$10^{20.5}$ cm^{-2} → low dust/metals is favoured

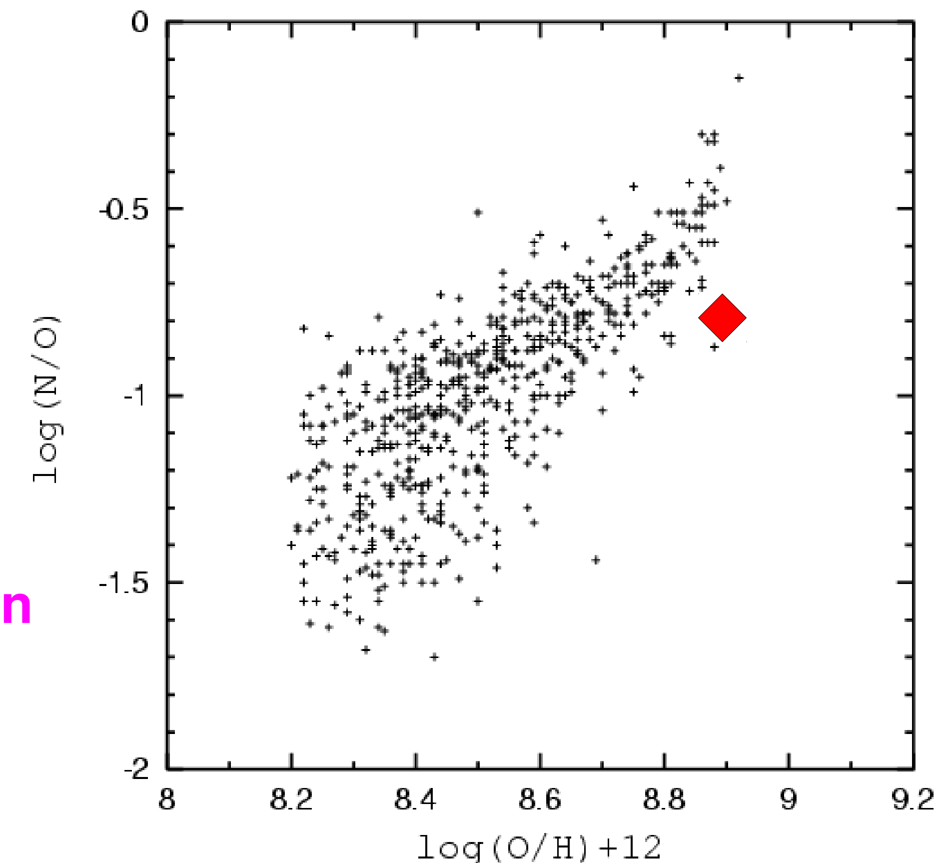
low number density = 1-10 cm^{-3}

moderately high T_{star} = 35000-40000 K

METALLICITY IS THE LEAST-CONSTRAINED PARAMETER:
reasonably good agreement for
$0.15\ Z_{sun} < Z < 1.0\ Z_{sun}$

However, high metallicity ($Z>0.5\ Z_{sun}$) models require very low N/O ratios (<1/5 solar), observed only in low-Z systems → **Z<0.5 Zsun**

Pilyugin, Thuan, Vilchez 2003



Conclusions & future work

Ionization models alone provide only weak constraints ($1/6\ Z_{sun} < Z < Z_{sun}$)
on the metallicity in the nebula around NGC 1313 X-2;
however, high metallicity models require an unphysically low N/O ratio.
Then

$$1/6\ Z_{sun} < Z < 1/2\ Z_{sun}$$

in rough agreement with empirical calibrations ($Z \sim 0.2$-$0.3\ Z_{sun}$)

Model improvements

include UV spectrum of accretion disc & reprocessed radiation
compare with models including shocks

Extend to other sources

suitable (though lower-quality) optical data are available for a few other sources,
such as IC 342 X-1, Holmberg II X-1, Holmberg IX X-1

Introduction

Models predict metallicity is important for ULX formation

examples

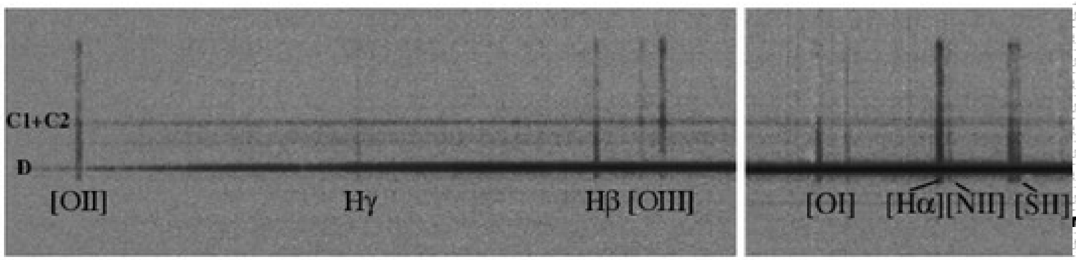
1) Mapelli et al. 2010 (previous talk; arXiv:astro-ph:1005.3548):
   low metallicity reduces stellar mass losses, enhancing the maximum possible M_{BH}

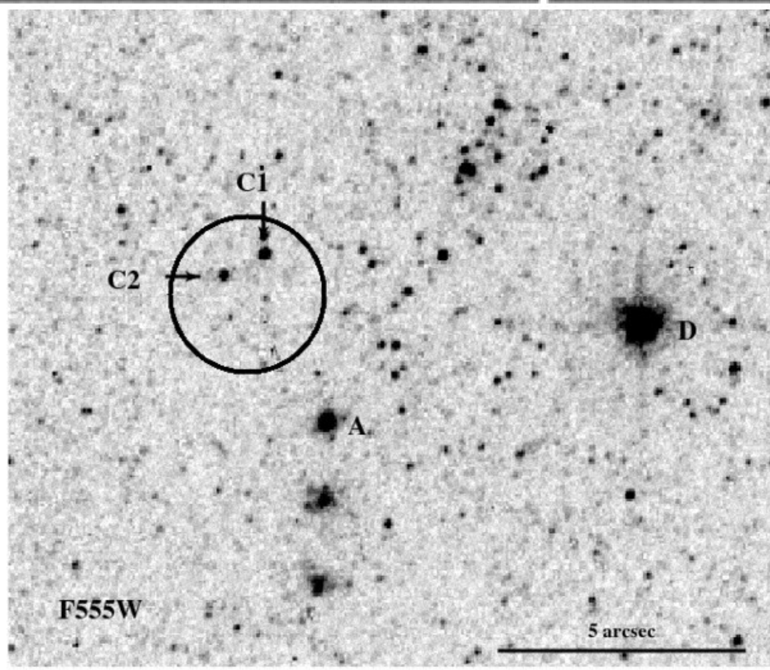
2) Linden et al. 2010 (arXiv:astro-ph:1005.1639)
   low metallicity enhances the probability of forming bright HMXBs (without really affecting M_{BH})

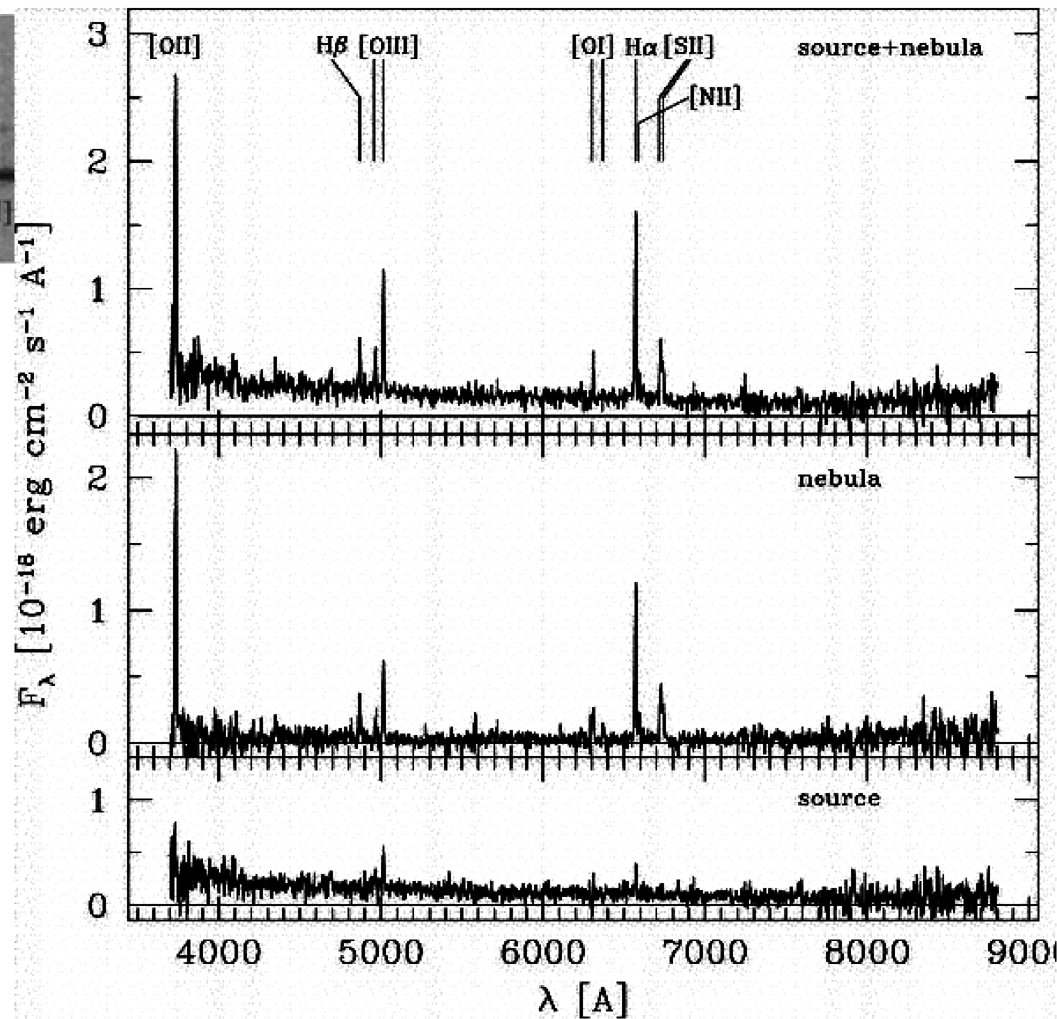
Measuring the local metallicity

Main tool: spectroscopic observations of the ionized nebulae around known ULXs

looked at data available for NGC 1313 X-2 (Mucciarelli et al. 2005, 2007)







Line intensities & Metallicity calibrations

Main observed metal lines [dereddened imposing I(Hα)/I(Hβ)=3.1]

I(OII 3727)/I(Hβ) = 6.03±1.34

I(OIII 4949)I(Hβ) = 0.47±0.15 **I(OIII 5007)]/I(Hβ) = 1.69±0.36**

I(OI 6300)/I(Hβ) = $0.93^{+0.23}_{-0.46}$

I(NII 6548)/I(Hβ) = 0.12±0.10 I(NII 6584)]/I(Hβ) = 0.53±0.30

I(SII 6725)/I(Hβ) = 1.95±0.42

I(Other lines) <~ 0.2 I(Hβ)

Metallicity calibrations

Pilyugin & Thuan (2005) and Pilyugin (2001) provide an empirical calibration of the metallicity proxy 12+log(O/H) in terms of the indexes

R_2=I(OII 3727)/I(Hβ) R_3=[I(OIII 4949)+I(OIII 5007)]/I(Hβ)

$R_{23} = R_2 + R_3$ $P = R_3 / R_{23}$

CAVEAT: disagreements up to a factor ~3 are possible between various R_{23} calibrations (e.g. with Edmunds & Pagel 1984) and grids of model HII regions (e.g. Kewley & Dopita 2002)

If we apply the PT05 calibration, we obtain 12+log(O/H)~8.2, i.e **Z~0.2 Z_{sun}**

BUT: standard empirical calibrations cannot be used because of the effects of the ULX X-ray emission

THEN: must build ionization models accounting for the ULX+companion star (and possibly other stars in the vicinity)

Modelling - 1

We use the photoionization code Cloudy (Ferland et al. 1998; www.nublado.org)

alternative: MAPPINGS (accounting for shocks)

however, collisional ionization due to the X-ray emission leads to similar features (e.g. strong OI 6300 and SII 6725 emission lines), especially if shocks are weak (v<200 km/s, Russell's talk)

Model parameters

Incident spectrum: Companion star

T_{star} : 8 values, 26200 → 48000 K,

appropriate Q(H); detailed spectra from model atmosphere library; same metallicity as the nebula

X-ray source

MCD(0.2 keV) + PL (Γ=2),

F_{MCD} =0.8F_{PL} , L(0.3-10 keV)=6x10^{39} erg s^{-1} ,

intrinsic N_H: 6 values, $N_{H,intr}$ =10^{19} → 2x10^{21} cm^{-2}

assumed to drop below 54.4 eV

Modelling - 2

Model parameters

Nebula composition:

Overall metallicity: 13 values, $Z = 1/40\ Z_{sun} \rightarrow 2\ Z_{sun}$

N/O ratio: 2 values, solar (Orion) or 1/3 solar

dust/metal ratio: 2 values, Orion or 1/10 Orion

Nebula geometry:

density: 5 values: $n = 1 \rightarrow 100\ cm^{-3}$

filling factor: 1/3

internal radius R_i = 1 pc (arbitrary)

external radius R_e such that

$$(R_e - R_i) \times n \times ff \times (Z/Z_{sun}) = N_{H,tot} - N_{H,gal} - N_{H,intr}$$

$$[N_{H,gal} = 4 \times 10^{20}\ cm^{-2},\ N_{H,tot} = 3 \times 10^{21}\ cm^{-2}]$$

"Galactic" vs "local" metallicity

Average galactic metallicity suffer from metal fluctuations within a galaxy:

- giant spirals exhibit metallicity gradients with radius
- variations of ±0.1 dex (i.e. ±25%) are possible even at fixed radius

Example: M 101 abundance profile (Pilyugin 2001)