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# Ultraluminous X-ray Sources forming in low metallicity natal environments

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**Abstract.** In the last few years multiwavelength observations have boosted our understanding of Ultraluminous X-ray Sources (ULXs). Yet, the most fundamental questions on ULXs still remain to be definitively answered: do they contain stellar or intermediate mass black holes? How do they form? We investigate the possibility that the black holes hosted in ULXs originate from massive (40-120 $M_{\odot}$) stars in low metallicity natal environments. Such black holes have a typical mass in the range $\sim 30-90 M_{\odot}$ and may account for the properties of bright (above $\sim 10^{40}$ erg s$^{-1}$) ULXs. More than $\sim 10^5$ massive black holes might have been generated in this way in the metal poor Cartwheel galaxy during the last $10^7$ years and might power most of the ULXs observed in it. Support to our interpretation comes from NGC 1313 X-2, the first ULX with a tentative identification of the orbital period in the optical band, for which binary evolution calculations show that the system is most likely made by a massive donor dumping matter on a $50-100 M_{\odot}$ black hole.

**Keywords:** Black holes, X-ray binaries
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## INTRODUCTION

When, at the beginning of the 80s, point-like, off-nuclear Xray sources were first detected in the field of nearby galaxies (see, e.g., [5]), it was immediately recognised that the luminosity of a subset of these objects was unusually large. If physically associated with their host galaxies, these UltraLuminous X-ray sources (ULXs) had an isotropic luminosity well in excess of the Eddington limit for spherical accretion onto a $10 M_{\odot}$ compact object. Thanks to the unprecedented capabilities offered by some of the major X-ray satellites (XMM, Chandra) and optical facilities (VLT, HST), nowadays more than 150 candidate ULXs have been detected and many of them have been studied in detail. Several pieces of observational evidence strongly suggest that a large fraction of these sources are accreting black hole X-ray binaries with massive donors (see, e.g., [23]).

The critical issue is then understanding what is responsible for the exceptionally high (isotropic) luminosity of these sources. Two main scenarios have been proposed. Firstly ULXs could be relatively normal stellar-mass ($\leq 20 M_{\odot}$) black holes (BHs) that are either anisotropically emitting X-ray binaries in a peculiar evolutionary stage [8], or are truly emitting above the Eddington limit via a massive, modified accretion disc structure (e.g.

photon bubble dominated discs [1]; two-phase super-Eddington, radiatively efficient discs [20]; slim discs [4]), or perhaps via some combination of the two [17, 9]. Secondly, the compact object could simply be bigger, and the accretion would be in the usual sub-Eddington regime. In this case the compact object would be an intermediate mass black hole (IMBH) with a mass in excess of $100 M_{\odot}$ (e.g. [2]).

Recently, [23] presented a critical revaluation of the available observational evidence concerning the BH masses in ULXs, suggesting that BHs of several hundreds to thousands $M_{\odot}$ are not required for the majority of ULXs. At the same time, models with stellar mass BHs may work for a large fraction of the ULX population, if the accretion flow has some degreee of beaming and is super-Eddington (e.g. [10]), but rather extreme conditions are needed to account for ULXs above a luminosity $\sim 10^{40}$ erg s$^{-1}$. Here we highlight an alternative scenario in which a proportion of ULXs contain $\sim 30-90 M_{\odot}$ BHs formed in a low metallicity environment and accreting in a slightly critical regime.

## A DIFFERENT INTERPRETATION

In our scenario bright ULXs may contain BHs with masses above 30-40 $M_{\odot}$ and up to $\sim 80-90 M_{\odot}$, formed from ordinary stellar evolution of massive ($40-120 M_{\odot}$) stars in a low metallicity natal environment. While this idea has already been suggested before (e.g. [15, 3, 22]), it has not yet been explored quantitatively in detail. In stars with main sequence masses above $\sim 25-30 M_{\odot}$, at the time of iron core collapse, the early accretion of the inner mantle before shock passage and the fallback of material afterwards cause the newly formed proto-neutron star to collapse to a BH after the supernova explosion. At solar metallicity, these fallback BHs reach at most $\sim 10 M_{\odot}$ as the stellar envelope is effectively removed through line-driven winds. For sub-solar metallicities, however, this mechanism becomes progressively less efficient and stars with masses above $\sim 30-40 M_{\odot}$ may retain rather massive envelopes at the time of explosion. The supernova shock wave then loses more and more energy in trying to unbind the envelope until it stalls and most of the star collapses to form a BH (direct BH formation) with a mass comparable to that of the pre-supernova star [7]. These may be the BHs hosted in some ULXs. Their mass would not be significantly larger than $\sim 80-90 M_{\odot}$ as above $\sim 100-120 M_{\odot}$ a star undergoes pulsational pair-instability in its core and most of the envelope mass is expelled.

According to the adopted mass loss history, the final mass of a massive star may differ up to a factor of $\sim 2$, or even more for clumpy winds. Additional uncertainty is caused by the dependence of mass loss on metallicity. A scaling law $\propto Z^{0.5}$ is often adopted for hot stars (see, e.g., [14]). Considering a star with an initial mass of $100 M_{\odot}$, its final mass may be in the interval $\sim 3-6 M_{\odot}$ for $Z \approx Z_{\odot}$ and $\sim 30-70 M_{\odot}$ for $Z \approx 0.1 Z_{\odot}$ [23].

Owing to their larger final masses, the fate of stars with sub-solar metallicity is likely to be be quite different from that of higher metallicity stars. Although different authors obtain different results for the mass of the compact remnant, it is not unreasonable to think that, if an envelope more massive than $\sim 30-40 M_{\odot}$ is retained at the time of explosion, a low metallicity ($Z \approx 0.1 Z_{\odot}$) star may collapse directly to form a BH of comparable mass. Significant stellar rotation (hundreds of km s$^{-1}$) may change this picture somewhat. However, if the core is not rapidly rotating, there is no good reason why most of the star should not collapse into a BH. At variance with IMBHs, the formation of these very massive stellar remnant BHs does not require an exotic, new mechanism but is referable to ordinary stellar evolution. At the same time, only modest beaming ($\sim 0.5$) or slight violations of the Eddington limit (a factor of a few) would be needed to account for the luminosity of bright (above $\sim 10^{40}$ erg s$^{-1}$) ULXs.

## TESTING THE MASSIVE BH INTERPRETATION

A crucial aspect of the interpretation of ULXs in terms of BHs from the direct collapse of low-$Z$, massive stars is the metallicity of the environment in which ULX binaries form. The scarce measurements available and the discrepancy between optical and X-ray data prevent at this stage to reach a definitive conclusion. In our proposed scenario ULXs should show some evidence of correlation (in terms of position and average luminosity) with low metallicity environments. So, one of the definitive tests of our proposal would be to survey ULX locations, and determine whether a relationship between ULX luminosity and local metallicity was evident in a large enough sample to provide statistically meaningful results. It is worth noting that, recently, [18] and [19] succeeded in performing dynamical mass measurements using Gemini and Keck spectra of the Wolf-Rayet optical counterpart of IC 10 X-1, a variable X-ray source in the the Local Group metal poor starburst galaxy IC 10. They find a BH mass in the range $23-33M_{\odot}$, which represents the most massive BH known to exist in a binary system and definitely corroborates our interpretation.

A crucial benchmark to test our interpretation is provided by the Cartwheel galaxy. This has a rather low metallicity ($Z \sim 0.05Z_{\odot}$, measured in the nebulae of the outer ring which are forming stars right now [6]) and hosts a large number of ULXs ($\sim 17$, [21]). We estimated the number of massive ($\geq 40M_{\odot}$) BHs $N_{BH}$ produced during a burst of star formation, assuming that they are distributed according to the stellar IMF [12]. For a star formation rate of $\sim 20M_{\odot}$ yr$^{-1}$ [13] and a duration of the star burst of $\sim 10^7$ yr, we find $N_{BH} \sim 10^5$ (with a slight dependence on the adopted IMF). The total mass ended up in massive BHs turn out to be $M_{BH} \sim 10^7 M_{\odot}$, corresponding to $\sim 5\%$ of the total stellar mass in the ring produced during the burst. Also, the production efficiency of ULXs ($N_{ULXs}/N_{BH}$) is estimated to be $\sim 10^{-4}$, which appears reasonable if compared to that obtained from independent estimates (from dynamical and/or binary evolution models [12]).

Finally, independent evidence in support of our interpretation may come also from NGC 1313 X-2, one of the most studied ULXs to date, located in a low metallicity environment ($Z \simeq 0.004-0.008$; e.g. [16] and references therein). Recently, [11] tentatively identified a modulation of $6.12 \pm 0.16$ d in the $B$ band HST lightcurve of this ULX. They interpreted the modulation as the orbital period of the system. Assuming that this identification is correct, we used all the optical data available for NGC 1313 X-2 and compared them with the evolution of an ensemble of irradiated X-ray binary models in order to constrain the nature of its compact accretor [16]. We restricted the candidate binary system to be either a $\sim 50-100M_{\odot}$ BH accreting from a $15M_{\odot}$ main sequence star or a $20M_{\odot}$ BH with a $12-15M_{\odot}$ giant donor. If the modulation of $\sim 6$ days is confirmed, a stellar-mass BH model becomes unlikely and we are left with the only possibility that the compact accretor in NGC 1313 X-2 is a massive BH of $\sim 50-100 M_{\odot}$, in agreement with the interpretation that it may contain a massive BH.

## CONCLUSIONS

We investigated in detail an alternative scenario in which bright ULXs contain BHs with masses above $\sim 30-40 M_{\odot}$ and up to $\sim 80-90 M_{\odot}$, produced by stars with initial, main sequence mass above $\sim 40 M_{\odot}$. The formation of these very massive stellar remnant BHs does not require an exotic, new mechanism but is referable to ordinary stellar evolution. For luminosities above $\sim 10^{40}$ erg $s^{-1}$, this would imply only modest violations of the Eddington limit, attainable through very modest beaming and/or slightly super-critical accretion. Measurements of the metallicity of the ULX environment and surveys of ULX locations looking for a statistically meaningful relationship between position, average luminosity and local metallicity will provide a definitive test of our proposal.

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