# IRRADIATION MODELS FOR ULTRA-LUMINOUS X-RAY SOURCES AND FITS TO HST DATA

**Chris Copperwheat[1], Mark Cropper[1], Roberto Soria[1,2], and Kinwah Wu[1]**

[1]Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
[2]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

## ABSTRACT

We have created a model to describe the optical emission from ULXs in terms of an irradiated companion star and disk. Here we detail our model, and present the initial results of its application to HST observations of three ULX optical counterparts. We list stellar parameters for the companion stars in these systems, and provide constraints on the black hole masses.

Key words: accretion, accretion discs; black hole physics; X-rays: galaxies; X-rays: stars.

## 1. INTRODUCTION

Ultra-luminous X-ray sources (ULXs) are point-like, non-nuclear sources with apparent isotropic luminosities greater than $10^{39}$ ergs s$^{-1}$. The brightest sources have X-ray luminosities in excess of $10^{40}$ ergs s$^{-1}$, implying bolometric luminosities of order $10^{41}$ ergs s$^{-1}$. This is significantly larger than the Eddington luminosity limit for an accreting stellar-mass black hole (BH). The nature of these objects are still unclear. The accreting object may be an intermediate mass black hole (IMBH) with mass $50 - 1000 M_{\odot}$, or it may be an ordinary stellar-mass BH with its emission beamed towards us. We seek to understand ULXs through observations of their optical counterparts. We find that optical/IR observations are powerful tools which complement X-ray observations in determine the properties and hence the nature of ULXs.

## 2. MODEL

We consider a binary model, with the compact object accreting material from a companion star. We assume the X-ray emission is isotropic, and hence take the IMBH interpretation as a starting point. The brightest ULXs require an accretion rate greater than that which could be supplied by a stellar wind, so we assume the matter is transferred onto the compact object through Roche lobe overflow. We constrain the geometry of the system so that the companion star is filling its Roche lobe. This constraint necessitates a small binary separation and a large companion star. A large amount of X-ray flux will be incident on the surface of this star, and the optical/IR characteristics of this star will be modified. The irradiation will induce intensity and colour shifts compared to normal stars, which we use as a diagnostic. We assume the system is in a quasi-steady state, and the irradiated surfaces are in thermal, radiative and hydrostatic equilibrium. We consider the effects of radiative transport and radiative equilibrium in the irradiated surface of the star and an irradiated accretion disk. We consider a plane-parallel model and adopt the radiative transport formulation of Milne (1926) and Wu et al. (2001) to describe the heated surface. We determine the total emergent radiation from a distorted, Roche lobe filling star numerically. We do the same for the disk, using a thin disk geometry.

The model is described more completely in Copperwheat et al. (2005). We extend this to use the isochrones produced by the Geneva stellar evolution models of Lejeune & Schaerer (2001) to provide stellar parameters which we use to produce new isochrones, with colours and magnitudes appropriate for an irradiated star and disk. We repeat this process as we vary the other important parameters, such as BH mass, and the inclination and orientation of the binary system.

## 3. APPLICATION TO ULX X-7 IN NGC 4559

HST observations have revealed eight candidates for the optical counterpart of ULX X-7 in NGC 4559; a ULX with $L_x \simeq 10^{40}$ergs s$^{-1}$ (Soria et al. , 2005). We find that three of the candidates (2, 3 and 4) are consistent with our model irradiated star and disk only when we use a very low inclination and a very high BH mass. If the inclination is such that the optical emission contains an appreciable disk component, these candidates do not fit with any BH and star combination. For most reasonable inclinations and binary phases, candidates 1, 5, 6 and 8 remain viable (Figure 1).

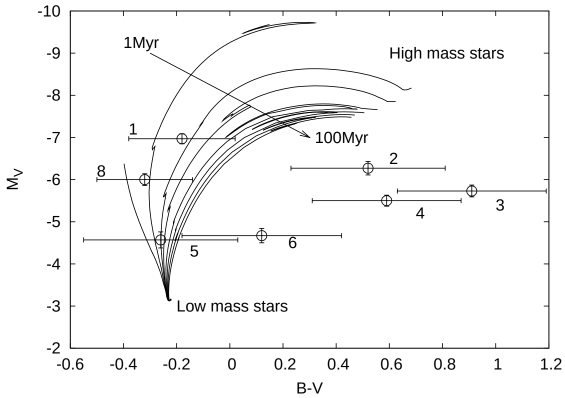


*Figure 1. A colour – magnitude diagram showing our theoretical isochrones plotted with the candidates for the counterpart of ULX X-7 in NGC 4559. We use here an inclination of* $\cos i = 0.5$ *and a BH mass of* $100 M_\odot$*. For these parameters, candidates 2, 3 and 4 are inconsistent with being the optical counterpart.*

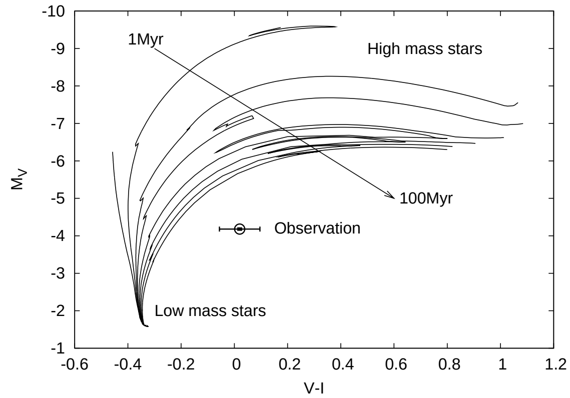


*Figure 2. A colour – magnitude diagram showing our theoretical isochrones plotted with the counterpart of ULX X-11 in NGC 3031. We use here an inclination of* $\cos i = 0.5$ *and a BH mass of* $10 M_\odot$*. The observation is inconsistent with the isochrones produced by our model for this BH mass.*

Soria et al. (2005) concluded that candidate 1 was the most likely counterpart to the ULX. The other candidates were found to be consistent with the unperturbed isochrones for stars with masses $10 - 15 M_\odot$ and ages of approximately $20$Myr. If we assume the companion star is also this age and that candidate 1 is indeed the counterpart, then by comparing the $20$Myr isochrone with the observed magnitudes we find the mass of the companion star to be $11 - 12 M_\odot$ and the radius to be $40 - 50 R_\odot$. We find also that when we use a BH mass of greater than a few hundred solar masses in our model, the $20$Myr isochrone we produce is inconsistent with the optical observations.

## 4. APPLICATION TO ULX-1 IN M101

Kuntz et al. (2005) examined HST observations of a unique counterpart to ULX-1 in M101 and suggested they were consistent with a B-type supergiant. Again, by applying our irradiation model we find it to be of an earlier spectral type, consistent with an F0-A0 supergiant, depending on the BH mass. In this case we cannot constrain the BH mass, but the lack of orbital variation observed by Kuntz et al. (2005) suggests a disk-dominated system, which may imply a more massive BH.

## 5. APPLICATION TO ULX X-6 IN M81

Liu et al. (2002) detailed HST observations of ULX X-6 in M81, and suggested it is an O8/O9 MS star with a mass of $26 - 50 M_\odot$ and an age of $< 5$Myr. When we apply our irradiation model, we find the optical observation to be consistent with a B-type MS star with a significantly lower mass ($5 - 8 M_\odot$) and an age that is up to an order of magnitude greater than that found by Liu et al. (2002), depending on the BH mass we use in our model. Additionally, we find that we can provide a lower limit on the BH mass. The field stars in the vicinity of the ULX have an age range of $1 - 100$Myr. We find the (V-I) colour of the observation is inconsistent with our theoretical isochrones in this range when we use a BH mass of less than $\simeq 100 M_\odot$ (Figure 2).

## 6. CONCLUSIONS

We find that by applying our irradiation model to the optical counterparts of ULXs, we can determine the parameters of the companion stars, and in some cases provide constraints on the mass of the black hole. We find the companion stars to be older, less massive and of a later spectral type than currently reported.

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