OPTICAL COUNTERPARTS OF ULTRALUMINOUS X-RAY SOURCES

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ABSTRACT

Despite much observational and theoretical effort little is presently known about the nature of the luminous non-nuclear X-ray sources which appear to largely surpass the Eddington limit of a few solar masses. Here we present first results of our OHP/ESO/CFHT optical survey of the environments of variable ultraluminous X-ray sources (ULX) in nearby galaxies. At the position of several ULX we find emission nebulae of a few hundred parsecs diameter, and which often show both low and high ionisation emission lines. The gas must therefore be either photoionized by hard XUV continua, or be shock-ionized in the expanding bubbles. The nebulae have kinematic ages of some million years and appear to be directly linked to the highly energetic formation process of the compact ULX or being inflated by ongoing stellar wind/jet activity. The discovery of intense He III λ4686 nebular recombination radiation together with comparatively strong [O I] λ6300 emission around the variable ULX in dwarf galaxy Holmberg II has allowed us to show that the interstellar medium actually ‘sees’ and reprocesses part of the ~10^{38} erg/s measured at X-ray wavelengths, if we assume isotropic emission. Strong beaming into our line of sight which has been advocated to avoid such high luminosities can thus be excluded, at least for this source.

Key words: X-ray sources; galaxies; supernova remnants; stellar wind bubbles; jets

1. Introduction

The luminosity function of compact accreting X-ray sources in the Local Group of Galaxies shows a well defined cut-off corresponding to the Eddington limit \( L_E = 1.3 \times 10^{38} \text{ erg/s} \) for a few solar masses. Beyond \( L_E \), stable accretion is no longer possible since radiation pressure would push off any material away from the compact star.

Nevertheless, there is now growing evidence for a class of non-nuclear X-ray sources in nearby galaxies which have individual luminosities higher than \( 10^{39} \) and up to some \( 10^{40} \) erg/s which, in parenthesis, is higher than the total high energy output of the Local Group of Galaxies. Such luminosities imply compact stellar masses of at least several tens to some hundred \( M_{\odot} \), if the Eddington limit is not to be violated; presently available stellar evolutionary models at solar metallicity on the other hand do not predict compact remnants that massive.

These objects have become much advertised under the label of intermediate-mass black holes, i.e. BHs with masses in between the stellar and the supermassive AGN type variety (c.f. Colbert & Mushotzky (1999) and they are also variously referred to as SuperEddington sources, Intermediate-luminosity X-ray Objects (IXO), and Ultraluminous X-ray sources (ULX). ULX are known to be a mixed bag of objects, including, apart from galactic foreground stars and background AGN, recent supernovae and very young SN remnants, to which the Eddington limit does of course not apply. However, many ULX - including several which have previously been thought to be SNR - are variable on short timescales of hours to days, suggesting a compact nature. Particularly impressive examples of ULX have recently been revealed with the Chandra observatory (e.g. Kaaret at al 2001, Bauer et al. 2001).

One possible solution to this puzzle has been to postulate highly anisotropic radiation in the form of ‘beaming’ towards the observer which would lessen the energy requirements, below \( L_E \) of a more conventional \( \leq 10M_{\odot} \) accretor (see, i.e. King et al. 2001).

X-ray spectra of several ULX observed with ASCA have successfully been fitted with the ”disc black body” model (often with an additional power-law component) assuming an optically thick accretion disk (Colbert & Mushotzky 1999, Makashima et al. 2000, Mizino, Kubota & Makashima 2001). The model works rather well for the spectra of galactic BH candidates, and this has often been taken as supporting evidence for a massive accreting BH nature of ULX. However, in this picture problems with, among others, the high inferred inner temperature parameter remain, which according to Mizino, Kubota & Makashima (2001) might possibly indicate the presence of either a rapidly spinning BH or the realization of an optically thick advection-dominated accretion flow close to the BH.

Many of the ideas about the nature ULX will remain speculation unless we have supportive evidence from observations at other wavelengths. Moreover, a multi-wavelength approach might help to understand formation and evolution of these interesting objects. We have therefore undertaken an observing program with the aim to iden-
tify the optical counterparts of ULX and to study the local stellar and interstellar population.

2. Optical Follow up: Prospects

ULX are only found outside the Local Group of Galaxies. This implies that their optical counterparts are probably rather faint, even if they are of the optically brightest massive X-ray binary X-ray (MXRB) variety. An O star companion (for which we assume \( M_V \approx -5 \)) would have \( V > 22 \) mag at a 3 Mpc distance of the closest ULX and beyond. This bleak perspective explains why not many optical follow-up observations of ULX have been reported until recently.

Potentially more spectacular are the possible interaction effects of X-ray sources with the diffuse interstellar medium. The best-known example is the radio nebula W 50 (i.e. Dubner et al. 1998) around the enigmatic SS 433. This nonthermal galactic nebula is a spherical shell with two lateral extensions, the “ears”, that are formed by interaction of the jets with the surrounding gas. The \( 60 \times 120 \) pc extent is that of a large supernova remnant which would be easily resolvable at several Mpc distance. Another possibility is photoionization of interstellar gas by the X-ray source. Until very recently, the only well-established X-ray ionized nebula (XIN - Pakull & Angelbault 1986) has been the Large Magellanic Cloud nebula N159F in which the black hole candidate LMC X-1 is embedded; see Figure 1.

Figure 1. The black hole candidate LMC X-1 and its X-ray ionized nebula N159F. \( H_\alpha \) emission is shown in red. The O 7 main sequence type optical counterpart \( (V \approx 14.6) \) is the fainter star of a close pair. The X-ray source is embedded in the \( 9 \times 13 \) pc \( H\alpha \) region N 159F which is part of the larger complex N159 in the Large Magellanic Cloud. The lower image is a section of a long slit spectrum centered on the optical counterpart. It has been filtered in the spatial direction (effectively removing the stellar continuum) in order to display the presence of the clearly extended narrow \( \text{He}\text{II}\lambda 4686 \) emission in the nebula. This emission is one of the hallmarks of an X-ray ionized nebula (see text). The strong nebular lines are, from left to right, \( H_\gamma \), \( H_\beta \), and \( \text{[O III]}\lambda\lambda 4959,5007 \).

3. Optical Observations

We have selected a sample of ULX in nearby galaxies (less than 10 Mpc distance) mainly from the list of Fourniol (1998) and also taking advantage of the compilation of HRI positions by Roberts & Warwick (2000). At the time of our observations no improved Chandra positions were known to us, so we took special care to correct positions by overlaying the HRI catalogue with digitized sky atlas images available at the Aladin facility (Bonmar et al. 2000) at Observatoire Astronomique de Strasbourg. Since most X-ray images contain several sources that can be associated with foreground stars or background AGN we have been able to obtain improved source positions with 3″ accuracy or better.

For obvious reasons, we have avoided ULX in edge-on galaxies or otherwise strongly absorbed (starburst) re-
regions. These sources need to be tackled with infrared instrumentation, and we note that IR follow-up work on the ULX in M 82 has revealed a young compact star cluster at the position of the enigmatic most luminous ULX in this starburst galaxy (see Ebisuzaki et al. 2001).

The optical observations were carried out during several runs between 1999 and 2001 at ESO NTT, CFHT, and using the Carelec spectrograph on the OHP 1.93m telescope. Of particular importance for the project was the possibility of the ESO Multi-Mode Instrument (EMMI), and the MOS and OSIS instruments at CFHT to quickly switch between direct imaging and spectroscopy. Thus we could obtain spectral information of any photometrically selected target in the same night. Standard filters included B, R and H\textsubscript{$\alpha$} bands, which allowed to obtain colors and net emission-line images. Reduction of the data and the production of color images was done using the MIDAS image processing software.

### Table 1. Some of the ULX in nearby galaxies for which we have obtained (interesting) optical observations. The designations of individual sources refer to the respective discovery papers. The following abbreviations are used: neb. = diffuse H\textsubscript{$\alpha$} emission centered on X-ray source; bub. = bubble-like nebula; H\textsubscript{II} = source within larger H\textsubscript{II} emission complex; * = possible stellar counterpart detected

| Galaxy   | ULX      | nature                        |
|----------|----------|-------------------------------|
| NGC 1313 | X-1; X-2 (X-3) | neb; bub.; (SN)               |
| IC 342   | X-1; X-2  | neb.; ?                       |
| Ho II    | X-1      | XIN                           |
| Ho IX    | X-1      | bub. *                        |
| M 81     | X-6      | neb.                          |
| IC 2574  | X-1      | H\textsubscript{II} *         |
| NGC 4559 | X-1; X-7 | ?; H\textsubscript{II} *       |
| NGC 4631 | H\textsubscript{II} |                        |
| NGC 4861 | X-1; X-2 | H\textsubscript{II}; H\textsubscript{II} |
| NGC 5204 | X-1      | bub. *                        |
| NGC 7793 | P13      | neb.                          |

4. Nebulae around ULX

In this section we present some of the newly detected nebulae, report on their optical spectra (if available), and comment on their possible nature. The images show continuum (R band) subtracted H\textsubscript{alpha} emission in yellow, B and R band images in blue and red, respectively. North is up, and East is to the left.

#### 4.1. IC 342 X-1

This nearby spiral (d=4.5Mpc) harbours two variable non-nuclear ULX that Kubota et al. (2001) have shown to follow low soft/hard X-ray spectral transitions that are believed to be characteristic for black hole candidates.

Positional information comes from the ROSAT HRI observations by Bregman, Cox & Tomisaka (1993). Figure 2 shows at the position of IC 342 X-1 a relatively isolated tooth-shaped nebula. The Tooth nebula has a diameter of 220 pc and its spectrum shows extreme SNR-like emission line ratios: \[[S II]/H\alpha = 1.2\] and \[[O I]\lambda6300/H\alpha=0.4\] (see Sect. 4).

#### 4.2. Holmberg IX X-1

This a close dwarf companion to the large spiral M 81, which explains that the X-ray source Holmberg IX X-1 is also known as M 81 X-9. At this position Miller (1995) noted the presence of the shell-like nebula LH 9/10 and proposed a possible (multiple) SNR nature, although he also noted that the diameter of 250 pc appeared to be rather large. However, analysing archival X-ray data from 20 years, LaParola et al. (2001) could show that the X-ray emission is highly variable with spectral changes reminiscent of of black hole candidates.

Figure 3 shows the H\textsubscript{$\alpha$} emitting nebula LH 9/10 to have a strikingly similar morphology to the radio images of barrel-shaped bilateral SNR (Gaensler 1998). The brightest object in the small group of blue stars noted by Miller (1995) has B\textlesssim22.1 mag and could be a early type main sequence star. Our spectra confirm the high \[[S II]/H\alpha\] and \[[O I]\lambda6300/H\alpha\] ratios reported by Miller (1995), but also show a more normal Balmer decrement H\textsubscript{$\alpha$}/H\textsubscript{$\beta$} rather than the curious value \textlesssim1.6 reported in that paper.
4.3. NGC 5204 X-1

Roberts et al. (2001) have recently described Chandra and ground based optical observations of the ULX in the Magellanic type galaxy NGC 5204. They proposed a comparatively bright $V=19.7$ mag stellar object to be the optical counterpart, but on the basis of an HST image the same authors (Roberts et al. 2002) now find several more, fainter stellar images which could also be associated with the X-ray source. Our multicolor images shown in Figure 4 reveal that the $B=21.9$ mag star located on the eastern rim of the error circle has very blue colors and should thus be considered a prime candidate.

Perhaps more interesting is our discovery of a H$\alpha$ emitting bubble with a diameter of some 360 pc. The ring is much larger then the "cavity" in the ionized gas reported by Roberts et al. (2002) now find several more, fainter stellar images which could also be associated with the X-ray source. Our multicolor images shown in Figure 4 reveal that the B=21.9 mag star located on the eastern rim of the error circle has very blue colors and should thus be considered a prime candidate.

4.4. NGC 4559 X-7, X-10 and IC 2574

NGC 4559 is another galaxy in common with the work of Roberts et al. (2002) reported at this conference. A previous ROSAT PSPC study was published by Vogler, Pietsch & Bertoldi (1997), and we use their source designa-
projected distance of 9 kpc from the nucleus and far from current star formation. For some reason it was once considered to be one of the most promising candidates of an Galactic cooling neutron star (Stocke et al. 1995).

Here we report that both NGC 1313 X-1 and X-2 imprint clear optical signatures of ULX activity on the interstellar medium in this galaxy. Beginning with X-2, Fig. E shows our NTT Hα image on which a beautiful elongated bubble nebula with a large diameter of some 400pc can be seen. The radial velocity confirms that it is indeed located in NGC 1313. A low resolution spectrum of this region (FWHM=2′′) has an intrinsic FWHM of 2′′ corresponding to 34 pc at the distance (3.2 Mpc) of Holmberg II (Pakull et al. 2002). Its luminosity $L_{H\alpha}\approx 2.5 \times 10^{36}$ erg/s. A narrow slit spectrum (Fig. E) of the Heel taken under more moderate seeing conditions (FWHM=2′′) is that of a high-excitation H II region typical for low metallicity ($Z/Z_{\odot} \sim 0.1$) starforming regions, except for the strengths of the [O I] $\lambda 6300$ and particularly $\lambda 4686$ emission which are truly outstanding.

Its luminosity $L_{\lambda 4686}$ is $2.5 \times 10^{36}$ erg/s. A narrow slit spectrum (Fig. E) of the Heel taken under more moderate seeing conditions (FWHM=2′′) is that of a high-excitation H II region typical for low metallicity ($Z/Z_{\odot} \sim 0.1$) starforming regions, except for the strengths of the [O I] $\lambda 6300$ and particularly $\lambda 4686$ emission which are truly outstanding.

We therefore propose that we are observing the optical manifestation of an X-ray ionized nebula (XIN), most probably somewhat diluted by more conventional ionization by O stars. The radial velocity agrees with that of the nearby H II regions in Holmberg II and proves that the X-ray source is indeed situated within that galaxy.

### 4.6. Holmberg II X-1

An even more outstanding demonstration of X-ray ionization is furnished by the interstellar environment of the L$_x \sim 10^{40}$ erg/s X-ray source in the M 81 group dwarf galaxy Holmberg II. As for the other ULX cases the high luminosity is derived from the observed flux presuming galaxian membership, and furthermore assuming that the source emits in an isotropic fashion.

To the best of our knowledge this source has first been discussed in the thesis works of Dickow (1995) and of Fourniol (1998). A more recent account can be found in Zezas, Georgantopoulos & Ward (1999). All authors agree that the ROSAT PSPC spectrum can satisfactorily be described by a power-law model (photon index $\Gamma=2.63$), but from a recent ASCA observation Miyaji, Lehmann & Hasinger (2001) favoured a less steep spectrum ($\Gamma=1.89$), or a thermal spectrum with $kT=4.8$ keV. Fourniol (1998) reported that a bremsstrahlung model with $kT=0.90 \pm 0.15$ was an even better representation of the PSPC data, and she also pointed out the likely association with the H II region HSK 70 (Hodge, Strobel & Kennicutt 1994); an important finding that has independently been noted by Zezas, Georgantopoulos & Ward (1999). The association is illustrated in Fig. 3 where we show the ROSAT error circle superposed on our CFHT multicolor image.

As the observations of Fourniol (1998) strongly suggested the presence of nebular high-excitation He II $\lambda 4686$ emission in HSK 70 we obtained a large-slit (slitwidth 6′′) spectrum displayed in the lower image of Fig. 4. which clearly shows that the $\lambda 4686$ emission is confined to the 'Heel' of the 'Foot Nebula', and that it has an intrinsically FWHM of 2′ corresponding to 34 pc at the distance (3.2 Mpc) of Holmberg II (Pakull et al. 2002). Its luminosity $L_{\lambda 4686}$ is $2.5 \times 10^{36}$ erg/s. A narrow slit spectrum (Fig. 4) of the Heel taken under more moderate seeing conditions (FWHM=2′′) is that of a high-excitation H II region typical for low metallicity ($Z/Z_{\odot} \sim 0.1$) starforming regions, except for the strengths of the [O I] $\lambda 6300$ and particularly $\lambda 4686$ emission which are truly outstanding.

We therefore propose that we are observing the optical manifestation of an X-ray ionized nebula (XIN), most probably somewhat diluted by more conventional ionization by O stars. The radial velocity agrees with that of the other nearby H II regions in Holmberg II and proves that the X-ray source is indeed situated within that galaxy. Compared to XIN N159F around the black hole candidate...
Figure 6. H$_\alpha$ image (upper) of the H II region HSK 70 in the dwarf galaxy Holmberg II with the 5′′ radius HRI error circle superimposed. The shape resembles that of an X-Rayed Foot where the emission is strongest in the Heel. The lower image is a 5′′ wide broad-slit spectrum (i.e. essentially slit-less; the dispersion is in the N-S direction and the spectral resolution is essentially determined by the seeing of 0′′8) which provides monochromatic images of the narrow nebular emission lines in the area. Note the presence of strong HeII$\lambda$4686 emission which is confined to the Heel.

LMC X-1 (c.f. Sect. 4) Holmberg II X-1 is \( \sim 30 \times \) more luminous, both in X-rays and in He II$\lambda$4686 emission.

Finally, in order illustrate the structure of the XIN we display in Fig. 7 various emission line intensities and the continuum as a function of position along a 1′′5 wide long-slit orientated E-W and centered on the Heel of the Foot. We see that the maximum of the $\lambda$4686 emission more or less coincides with the peak of the Balmer emission and with a non-resolved, B=20.6 mag continuum source. However, closer inspection reveals that the He II$\lambda$4686/$\beta$ ratio (not shown here) clearly peaks towards the East of the line maxima. On the other hand, the [O I]$\lambda$6300 intensity distribution is clearly shifted towards the "Toes". In Section 5 we will argue that this is just what one would expect for the case that the nebula is density bounded in the eastern direction.

5. REMNANTS, WINDS AND XIN

The discovery of nebula around a significant fraction of ULX undoubtedly provides clues to their formation and to their mass-loss history, either though explosive events or by stellar winds or jets. ULX NGC 1313 X-2 will serve as an example for what can be deduced from the optical observations. Assuming that the 400 pc diameter nebula is the remnant of a supernova-like event which created the compact star we can use the well-known relations of
Figure 8. Intensity distribution of various emission lines and the continuum as a function of pixel position (1 pix=0.28) of a long-slit oriented East (left) - West (right). Relative intensities are not drawn to scale. Note in particular the relative shift between the [O I]6300 and He II\lambda4686 emission regions, where the indicating the presence of warm O\(^0\) towards the 'Toes'.

SNR evolution. The large extent clearly suggests that the remnant must be in the pressure driven snowplough phase, where the evolution of the outer shock proceeds by ( Gioffri, McKee & Bertschinger 1988)

\[ R = 93 \text{ pc} E_{52}^{0.22} n^{-0.257} t_6^{0.3} \]

\[ v = 28 \text{ km/s} E_{52}^{0.22} n^{-0.257} t_6^{-0.7} \]

where R is the radius and v the expansion velocity of the remnant after 10\(^6\) t\(_6\) yrs, E\(_{52}\) the explosion energy in units of 10\(^{52}\) erg and n is the interstellar density (cm\(^{-3}\)) into which the remnant expands. If both R and \(v\) can be measured, we can solve for E

\[ E = 6.8 \times 10^{43} \text{ erg} \]

\[ R_{pc}^{3.16} v_{\text{km/s}}^{1.36} n^{-1.16} \]

The density can estimated using the Dopita & Sutherland (1995) scaling relations of the total radiative H\(_2\) flux (including radiative precursor) emitted by interstellar shocks of 100 v\(_{100}\) km/s velocity

\[ F_{\beta} = 1.7 \times 10^{-5} v_{100}^{2.35} \text{ erg cm}^{-2} \text{ s}^{-1} \]

Plugging in the observed values for the NGC 1313 X-2 nebula (R=200pc v=80 km/s L\(_\beta\) \sim 1 \times 10^{37} \text{ erg/s}) we arrive at an age of \(\sim 0.8\) Myr, density \(\sim 0.2\) cm\(^{-3}\) and an impressive explosion energy of \(\sim 3 \times 10^{52}\) erg/s.

Alternatively, we could imagine that the bubbles are being inflated by ongoing stellar wind or jet activity, such as observed in SS 433 (c.f. Sect. 3). Although in this case the numerical factors and exponents in Eq. (1)-(3) change somewhat, the total energy requirements and active lifetimes would be about the same. The implied wind/jet luminosity (= 0.5\(M v^4_{jet}\)) of 1.5 \(10^{39}\) erg/s can thus only be generated in a relativistic outflow, such as from the SS 433 system.

We now turn to the physics of X-ray ionized nebulae, and to what we can learn about the sources that excite them. This field was pioneered by (Tarter, Tucker & Salpeter 1969) and applied to XIN N159F/LMC X-1 by (Pakull & Angebault 1986). The main difference to more conventional H II regions is the absence of sharp transitions between ionized and neutral plasma at the outer boundary (Strömgren spheres), since X-rays are not very efficiently absorbed. This creates an extended warm (electron temperature T\(_e\) \sim 10\(^4\) K) weakly ionized zone, in which neutral atoms can be collisionally excited.

The emission from highly ionized gas like the He\(^{++}\) \rightarrow He\(^+\) A4686 recombination line close to the source, and from forbidden transitions of neutrals like [O I]6300 in the outer extended zones are thus the hallmarks of XIN. Note that A4686 acts as a photon counter of the emitted source flux in the He\(^+\) Lyman continuum between 54 eV and about 200 eV (Pakull & Angebault 1986). This also implies that few A4686 photons will be emitted if the source is intrinsically weak or absorbed below \(\sim 100\) eV.

Taking advantage of the widely used photoionisation code CLOUDY developed by Gary Ferland (1990) we have calculated a grid of XIN with a range of bremsstrahlung input spectra (including various contributions of normal stellar ionizing continua), nebular density and metallicity. These were confronted with our spatially resolved spectra of the Heel Nebula in Holmberg II. The results can be summarized as follows (see Pakull et al 2002):

- We confirm the photon counting property of the A4686 line irrespective of metallicity, density or presence of O star continua.
- The ionizing X-ray continuum is diluted by more conventional O star radiation. This lowers the relative strength of A4686 as compared to H\(_\beta\), and decreases [O I]6300/H\(_\alpha\) due to photionization by O stars of O\(^0\) star in the extended warm zone of the XIN.
- The fact that the A4686 and A6300 emitting regions do not spatially coincide practically excludes the remote possibility of strong shock excitation in the nebula.
- The absence of [O I]A6300/H\(_\alpha\) emission to the east of the heel (Fig. 5) can be understood by a density-bounded geometry in that direction.
- For an assumed thermal bremsstrahlung spectrum of temperature kT the observed A4686 luminosity of 2.5 \(10^{36}\) erg/s implies that the nebula actually "sees" (and reprocesses) the unabsorbed He\(^+\) Lyman continuum of such a spectrum having an X-ray luminosity of some 3 \times 10^{39} \times kT_{keV} \text{ erg/s}. Accordingly we deduce for the range of temperatures summarized in Sect. 4.6 an expected X-ray output L\(_X\) = 0.3 - 1.3 \(10^{40}\) erg/s, which is in agreement with the directly observed luminosity.
Therefore we think that our data exclude significantly non-isotropic beaming for Holmberg II X-1.

To conclude this Section we emphasize that optical spectra of fast interstellar shocks (e.g. Dopita & Sutherland 1993) which are possibly present in some of our ULX nebulae, do often look quite similar to XIN. Compared to normal H II regions both display enhanced forbidden lines of neutral species, and He II λ4686 can become detectable for shock velocities larger than 300 km/s. The inclusion of radiative precursors of shocks can furthermore lower a very high electron temperature in the post shock O++ region (observable from the the well-known λ5007/λ4363 line ratio) to more conventional 1-2×10^4 K.

6. Conclusions

We are aware of the fact that we have just begun to scratch the surface of a new (optical) observational approach to study the enigmatic ULX, and possibly to understand formation and evolution of luminous compact X-ray sources in general.

We find, like other authors before us, that ULX do preferentially occur in, or close to star forming regions, and that some nearby starbursts harbour several of them. Yet, the bubbles in Holmberg IX and NGC 1313 are located far from other young objects. Maybe there are two populations of ULX?

Among the more quiet galaxies, ULX appear to prefer the more metal-poor dwarfs. Examples are the M81 group, with only one such object in M81 itself, but ULX are seen in IC 2574, NGC 2403, Holmberg II and Holmberg IX; the M101 group has only the ULX in NGC 5204... It is well-known that massive stellar evolution proceeds differently in such environments (Maeder 1992), mainly because wind loss is much reduced in low-metallicity stars during the pre-SN evolution. This naturally leads to much more massive cores that accordingly might collapse to more massive black holes.

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