The young open cluster NGC 6231: five years of investigations*

H. Sana[†], G. Rauw[‡] and E. Gosset[‡]

Institut d'Astrophysique et de Géophysique, Liège University, Belgium

Abstract: In this contribution, we present an overview of the main results obtained by the Liège multiwavelength (in the X-ray and optical domains) campaign on the young open cluster NGC 6231. We probe the distribution of the O star properties, and especially their binary nature. In this regard, we revise the O-type binary fraction and we briefly discuss the distribution of the binary parameters. We then present the latest developments of the canonical $L_{\rm X} - L_{\rm bol}$ relation. We discuss the causes of the observed deviations from this relation and of the X-ray variability among O-type stars. Probing the population of low mass pre-main sequence stars detected in the X-ray domain, we propose a scenario for the star formation history in NGC 6231.

1 Introduction

Located at about 1.6 kpc from the Earth, NGC 6231 hosts a rich early-type star population and has been chosen as the target of an extended multiwavelength campaign (in the optical and X-ray domains) by the Liège team. Since 1999, we have been acquiring high resolution spectra of most of the early-type stars of the cluster. The bulk of our data set was obtained with the ESO FEROS spectrograph. In 2001, the cluster was also the target of an X-ray monitoring campaign using the XMM-*Newton* observatory. Of a nominal duration of 180 ks, the campaign actually consisted of six separate pointings spread over a 5-day duration. This particular schedule aimed at the study of the variations of the X-ray flux of the early-type stars on different time-scales. More details about the Liège multiwavelength campaign can be found in Sana (2005).

2 Optical spectroscopy

Thanks to the high quality of our FEROS spectra, we have been able to provide an updated/new spectral classification for all the O-type stars in the XMM-*Newton* field of view (fov), and for 15 B-type stars. We derived SB2 orbital solutions for all 5 short period ($P < 6$ d) O-type

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[†]FNRS Research Fellow [‡]FNRS Research Associate

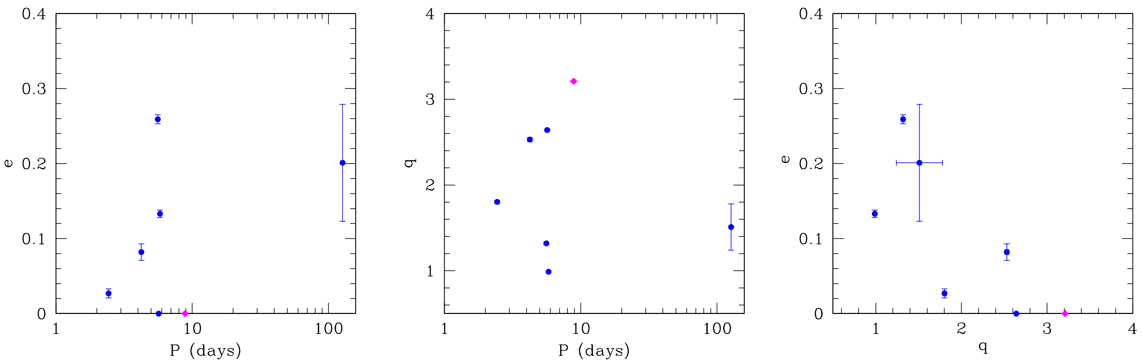

Figure 1: Distribution of various orbital and physical parameters (period, eccentricity, mass ratio) of the O-type binaries in NGC 6231. The diamond indicates the WR system HD 152270.

binaries (some of them for the first time). We also showed/confirmed that four other O-type objects were definitely longer period binaries ($P \sim$ a few months to a year) and we detected the signature of the secondary component for three of them. We are currently monitoring these objects to definitely upgrade their orbital solutions. Beside the 10 binaries (including the WR system WR 79), we also monitored the six remaining, presumably single, O-type stars of the cluster. We unveiled line profile variations (LPVs) for three of them, although these LPVs are probably not related to a binary nature. Accounting for the Wolf-Rayet system, we derive a binary fraction $f = 10/16 \sim 63\%$ for the O-type star population in NGC 6231. This is a somewhat lower value compared to the fraction $f \sim 79\%$ obtained by Garcìa & Mermilliod (2001, GM01 hereafter). This difference probably results from the lower quality of their spectra, as well as from their scarcer follow-up which did not allow them to distinguish RV-shifts most probably due to LPVs from those resulting from an orbital motion.

Fig. 1 presents the obtained distributions of the periods (P), eccentricities (e) and mass ratios (q). These are clearly different from those proposed by GM01. In particular, all the binaries have an eccentricity below 0.3 while GM01 obtained eccentricities ranging from 0.2 to 0.6. Reasons for this were already discussed in Sana et al. (2003) in the case of CPD $-41°7742$. The same discussion applies for the other systems as well. From Fig. 1, we note that the shortest period systems have a small eccentricity while the latter can be larger for longer periods. No obvious trend comes out of the period vs. mass-ratio diagram. It however indicates that the largest mass-ratio in our sample is about 3, which might reflect an observational bias. On the other hand, the eccentricity vs. mass-ratio diagram suggests the existence of an $e - q$ relation similar to the $P - e$ one. Systems with a higher mass-ratio indeed tend to display a smaller eccentricity. Accounting for the fact that all the points in the diagram come from binaries in the same cluster, thus with similar ages, this suggests that larger mass-ratio systems tend to circularize faster and, hence, that tidal dissipation is more efficient in such a configuration. Of course, there is so far only a limited sample of points in the diagram. We checked for SB2 O-type binaries in the 9th Spectroscopic Binary Catalogue and put them in the different diagrams. We observed the same trends for the first two plots of Fig. 1 while neither clear confirmation nor rejection of the existence of an $e - q$ relation could be established. It is possible that including objects from different ages actually hides an underlying relation. The next step in our analysis will be to check the quality of the different orbital solutions in the 9th Spectroscopic Binary Catalogue as well as to investigate the possible effect of the age on the obtained $e - q$ diagram.

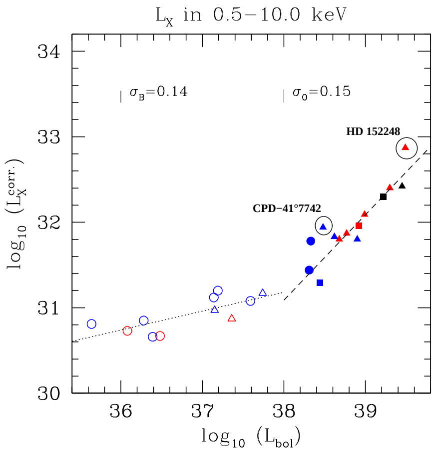

Figure 2: ISM-absorption corrected X-ray luminosities in the 0.5-10.0 keV band plotted vs. bolometric luminosities. Spectral type: O (filled symbols), B (open symbols). Luminosity class: supergiant (black), giant (red), main sequence (blue). Multiplicity: binary (triangles), single RV-variable star (squares), single constant-RV star (circles). Best-fit *canonical* relations for O (Eq. 1) and B (Eq. 2) stars are indicated by the dashed and the dotted lines respectively. σ_O and σ_B give respectively the related 1-σ deviation.

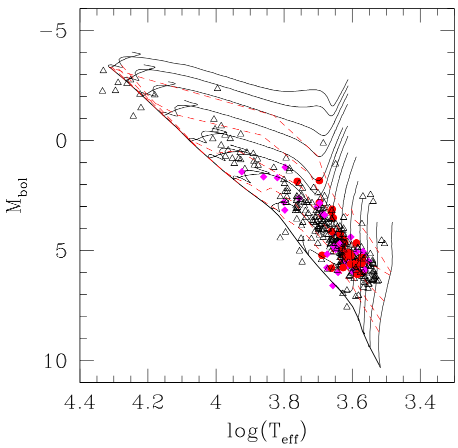

Figure 3: H-R diagram of the EPIC sources with optical counterparts in the Sung et al. (1998) catalogue. Evolutionary tracks from Siess et al. (2000) for masses of 0.2, 0.3, 0.4, 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0 and 7.0 $M_\odot$ are overplotted. Filled dots, filled diamonds and open triangles indicate respectively Hα emitting stars, Hα candidates and stars with no evidence for emission. The dashed lines correspond to isochrones for ages of 0.5, 1.5, 4.0, 10.0 and 20.0 Myr.

3 X-ray properties of the OB star population

All the O-type stars are detected as bright and relatively soft X-ray emitters while only about 20 % of the B-type stars can be associated with an X-ray source. Fig. 2 presents the obtained L_X vs. L_{bol} diagram, considering only the sources with good quality spectra (see details in Sana et al. 2006). Clearly, the O-type stars draw a linear relation in the log − log plane. However, a couple of points display an enhanced extra X-ray emission compared to the expected linear relation. The two systems HD 152248 (Sana et al. 2004) and CPD −41°7742 (Sana et al. 2005a) are definitely colliding wind binaries for which we expect the wind interaction to produce a substantial amount of X-rays. Excluding those two points, a least-square fit yields:

$$\log L_X - \log L_{bol} = -6.912(\pm 0.153) \qquad (1)$$

This corresponds to a dispersion of the X-ray luminosity of about 40% around this new *canonical* relation. Within our sample, significant variability of the X-ray flux is solely observed for binaries, suggesting a wind interaction origin. This mechanism is also the only identified phenomenon that produces a significant deviation from the *canonical* relation.

Regarding the B-type stars, only about 20% of them could be associated with an X-ray source. They also seem to draw a line in the log − log plane and a least-square fit yields:

$$\log L_X = 0.22(\pm 0.06) \log L_{bol} + 22.8(\pm 2.4) \qquad (2)$$

Note that we again observed a limited dispersion. However, the X-ray spectral properties are very similar to those of PMS stars and about one third of the sources displays flaring-like activity during the 180 ks of our campaign. It is therefore difficult to definitely decide whether the X-ray emission is associated to the B-type stars or if it is produced by PMS stars either located within a binary system or lying by chance along the same line of sight.

4 The optically faint X-ray sources

Beside the early-type stars, the combined EPIC image reveals several hundreds of sources (Sana et al. 2005b). Most of them are fainter but harder and are thought to be associated with PMS stars in the cluster. In total, about 80% of the detected X-ray sources could be associated with optical/IR counterparts, using different existing catalogues and, in particular, the UBV(RI)$_C$ H$_\alpha$ catalogue of Sung et al. (1998). For the latter objects, the location of the optically identified X-ray sources in the H-R diagram is presented in Fig. 3. Comparing with the PMS evolutionary tracks and isochrones from Siess et al. (2000), we get an idea of the masses and evolutionary ages of these objects. Most of them are low mass stars ($M < 2$ M$_\odot$) that started their formation about 2 to 5 Myr ago. However, the distribution of ages suggests that the star formation in NGC 6231 could have started at least 10 Myr ago at a relatively slow rate. This rate then slowly increased to culminate in a *starburst*-like event about 2 to 4 Myr ago, an epoch corresponding to the formation of the massive stars too.

5 Conclusions

We summarized the main achievements of the Liège multiwavelength campaign on the young open cluster NGC 6231. In the optical, our long-term monitoring of most of the early-type stars provides the best set of constraints obtained so far on their orbital and physical parameters. Clearly, it forms a firm basis for the X-ray analysis. On the other hand, the present XMM-*Newton* campaign is certainly one of the deepest X-ray observations of such a young cluster. It reveals a crowded fov, most sources being probably PMS stars, and provides insight into the cluster star formation history. Regarding the O stars, the limited dispersion observed around the *canonical* relation compared to the dispersion obtained by previous studies (e.g. Berghöfer et al. 1997) notably suggests that the *intrinsic* X-ray emission of single O-type star is rather stable, both in terms of brightness and variability. The present sample is however formed by a limited number of stars. The comparison of the present results with those derived in a homogeneous way from the studies of other young clusters will be of major interest.

Acknowledgements

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