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Stellar Activity in the NGC 2451 Clusters

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Abstract. We present results of our combined X-ray and optical study of NGC 2451, which actually consists of two different stellar clusters situated along the same line-of-sight at distances of 190 and 360 pc, respectively. Based on ROSAT X-ray observations and on our extensive optical CCD BVR-photometry we are able to identify 113 stars down to spectral class M as member candidates of the two NGC 2451 clusters. Their general X-ray properties are consistent with an age in the range 50 to 100 Myrs. The nearer of the two clusters is especially interesting since it ranks among the ten nearest clusters and is supposed to be of lower metallicity than solar.

1. Introduction

Stellar clusters provide homogeneous samples of stars of the same age, distance, and chemical composition. The investigation of clusters of different age allows us to study the evolution of stellar properties like, e.g., activity, rotation, or lithium abundances. Whereas a good coverage of age has already been achieved, this is not the case for metallicity. NGC 2451 may be an especially interesting object since it turned out to be one of the nearest clusters and is reported to have a lower metallicity than the Sun (Lynga & Wramdemark 1984, Lynga 1987).

A major problem is the identification of cluster members. Proper motion studies only exist for the brighter stars. However, the identification of cluster members by means of their mostly strong X-ray emission has been proved to be a powerful tool and can be applied here as well.

2. The Nature of NGC 2451

Various photometic studies of NGC 2451 (Williams 1966, 1967a,b, Feinstein 1966, Eggen 1983, 1986, Lynga & Wramdemark 1984, Pastoriza & Röpke 1983, Claria 1985) resulted in discordant values for distance and age and started a debate on the nature and even physical existence of the cluster. The investigation of kinematical data by Röser & Bastian (1994) lead to the idea of two different clusters in the same line of sight, which was later confirmed by various authors (Platais et al. 1996, Baumgardt 1998, Carrier et al. 1999, Robichon et al. 1999).

Currently, the best distance values are 190 pc for the nearer cluster NGC 2451 A and 360 pc for the more distant cluster NGC 2451 B.

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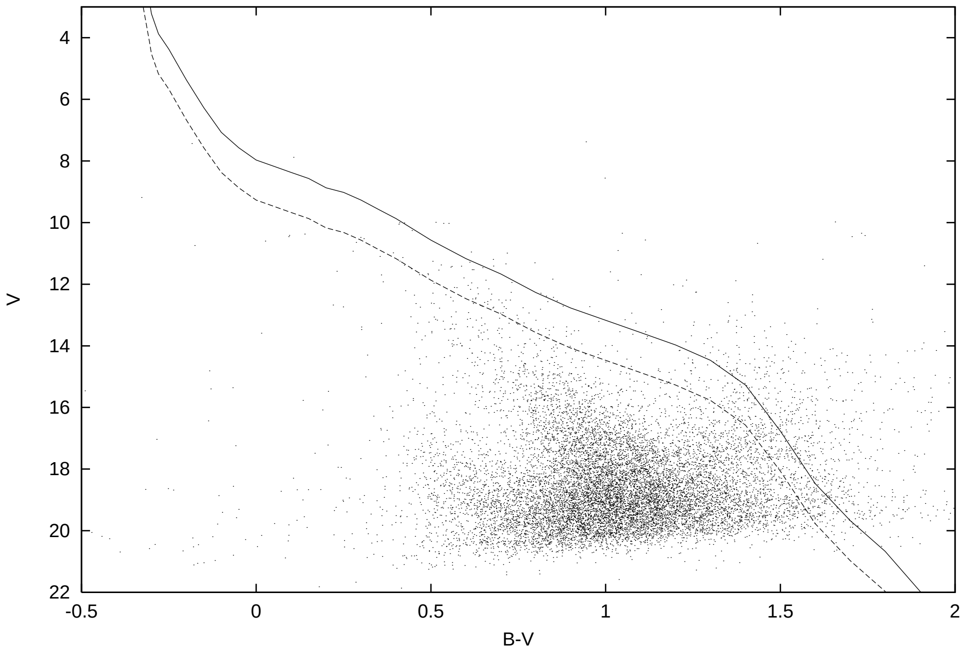

Figure 1. Colour-magnitude diagram of the stars in the inner NGC 2451 cluster region. The ZAMSs expected for 190 pc (solid line) and 360 pc (dashed line) distance are also shown.

3. Observations

3.1. X-ray Observations

ROSAT X-ray observations in pointed mode were carried out at three different epochs. In order to improve the sensitivity the two PSPC pointings were also merged to an artificial pointing C.

Table 1. Journal of ROSAT X-ray observations

Pointing	Sequence ID	Detector	Date	Exposure time
A	WG201217p	PSPC	1992–11–12	9.22 ksec
B	WG201576p	PSPC	1993–10–10	10.32 ksec
C	= A + B	PSPC	—	19.54 ksec
H	WG202531h	HRI	1996–11–1-3	57.58 ksec

Data reduction was performed by EXSAS. The source detection for each ROSAT pointing was executed in three different energy passbands: broad (0.1 - 2.4 keV), soft (0.1 - 0.5 keV), and hard (0.6 - 2.1 keV). The detection limit (3σ, pointings C and H) is $\approx 4 \times 10^{28}$ erg s^{-1} for cluster A and $\approx 1 \times 10^{29}$ erg s^{-1} for cluster B. Altogether, after checking for identical sources, there are 188 individual X-ray sources detected by ROSAT.

Pointing	broad band	soft band	hard band
A	105	32	110
B	87	24	100
C	122	35	142
H	87	–	–

Table 2. Numbers of detected X-ray sources

3.2. Optical Photometry

BVR CCD-photometry was carried out during 5 nights in December 1997 at the ESO 0.9m Dutch telescope, using a TK512CB 510×510 pixel chip yielding a field-of-view of 3.8×3.8 square arcmin. Exposure times are 15/90 sec in B and 10/60 sec in V and R, each. Data reduction was performed by using standard IRAF routines and DAOPHOT. Altogether, photometric data for 13307 stars in the inner cluster region were collected. The typical photometric errors are 0.03 at V=12 and 0.08 at V=18. Fig. 1 shows the colour-magnitude diagram.

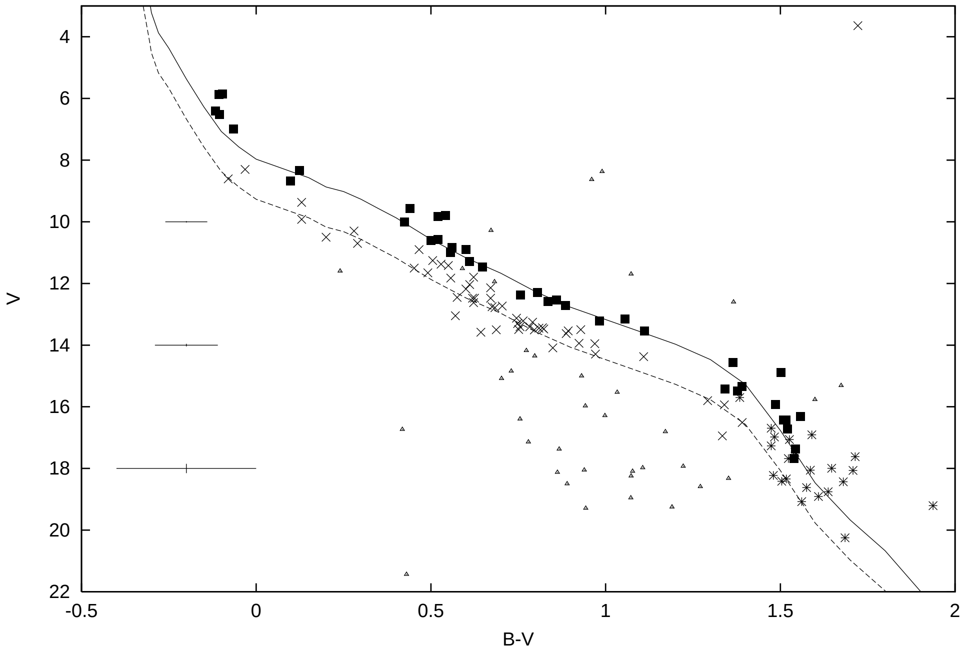

Figure 2. Colour-magnitude diagram of the stars identified with X-ray sources. Indicated are probable members of NGC 2451 A (squares), NGC 2451 B (crosses), faint stars belonging to either of the clusters (asterisks), and non-members (triangles). Note the gap in the main-sequence population between B–V = 1.1 and 1.3 (∼ K dwarfs) and the presence of an X-ray bright K-type supergiant member (= c Pup).

4. Results

4.1. Identification of Cluster Members

The identification of X-ray sources with optical counterparts is based on positional coincidence, taking into account positional offset, significance of the source, detector resolution, and presence of other nearby stars. All stars identified with X-ray sources and lying close to the expected main-sequences in the colour-magnitude diagram are regarded as probable cluster members. 38 stars are believed to be members of NGC 2451 A, 53 stars as members of NGC 2451 B, 22 faint stars are probable members of either of the two clusters, but due to larger photometric errors it is not clear to which of them they belong. 36 stars identified with X-ray sources are probably non-members (Fig. 2). The remaining 39 X-ray sources could not be identified.

4.2. Detection Rate

Within the magnitude interval V = 10 to 13 (i.e., spectral types F5 to K2 for NGC 2451 A and A7 to G5 for NGC 2451 B) 36 of 91 stars (40%) are detected in X-rays (cf. $\sim$ 80% for α Per; Randich et al. 1996). The lower detection rate may result from stronger contamination by non-members and from the lack of additional membership information like proper motions.

4.3. X-ray Luminosities and Distribution Function

From the mean X-ray luminosities, given in Tab. 3 for different mass ranges of main-sequence stars of NGC 2451 and similar clusters, it seems as if the age of both NGC 2451 clusters is between that of IC 2602/IC 2391 and the Pleiades, i.e., about 50 to 100 Myrs. Whether the slightly higher X-ray luminosities of NGC 2451B correspond to a younger age or are a selection effect due to its larger distance, is not clear (Fig. 3).

Table 3. Mean X-ray luminosities of the stellar population of NGC 2451 and similar clusters for different B-V (i.e., mass) ranges

Cluster	Age (Myrs)	B–V 0.35...0.75	B–V 0.75...1.25	B–V >1.25	Ref
NGC 2451 A	(50?)	29.57	29.30	29.07	1
NGC 2451 B	(50?)	29.73	29.72	29.42	1
IC 2602	30	29.85	29.86	29.18	2
IC 2391	30	29.38	29.45	29.38	2
Pleiades	70...120	29.40	29.40	29.08	2

References: 1 this work, 2 Randich et al. (1995).

The cumulative X-ray luminosity distribution functions for both clusters and different stellar mass ranges are shown in Fig. 4.

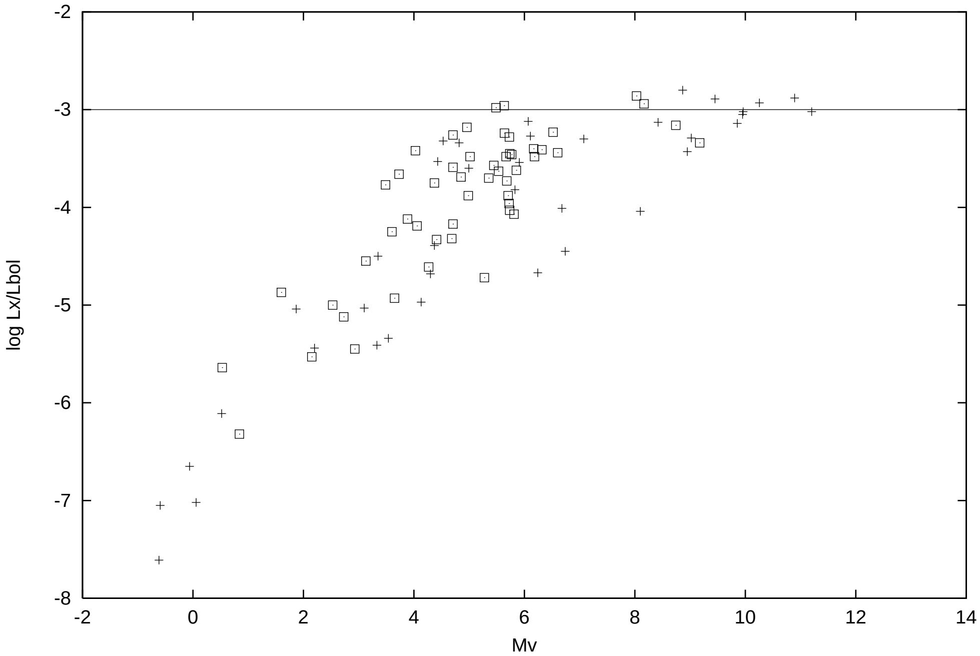

Figure 3. Normalized X-ray emission vs. absolute visual magnitude for NGC 2451 A (plusses) and NGC 2451 B (squares).

4.4. Variability Studies

Of the 64 X-ray sources identified as probable cluster members (either NGC 2451A or B) *and* detected in *both* PSPC pointings separated by 11 months, 27 (=42%) show long-term variations exceeding the errors in the count rates. Four large X-ray flares occured during the ROSAT observations in F-, G-, and two M-type stars, which are subject of a separate investigation.

5. Conclusions and Outlook

Also in the case of NGC 2451 identifying cluster members by means of their X-ray emission turned out to be a successful method. The probable members populate two main sequences at distances of 190 and 360 pc. The mean X-ray luminosities and distribution functions suggest an age in the range 50 to 100 Myrs consistent with the presence of early B-type stars. The more distant cluster is possibly slightly younger than the nearer one.

A more detailed investigation of ages, distances and reddening will be performed by means of isochrone fitting. Furthermore, a spectroscopic study concerning the metallicity and lithium abundances in the NGC 2451 clusters is currently in preparation. Since NGC 2451 A ranks among the ten nearest clusters and is rather young it may also be a good candidate for an independent age determination by means of the lithium depletion method.

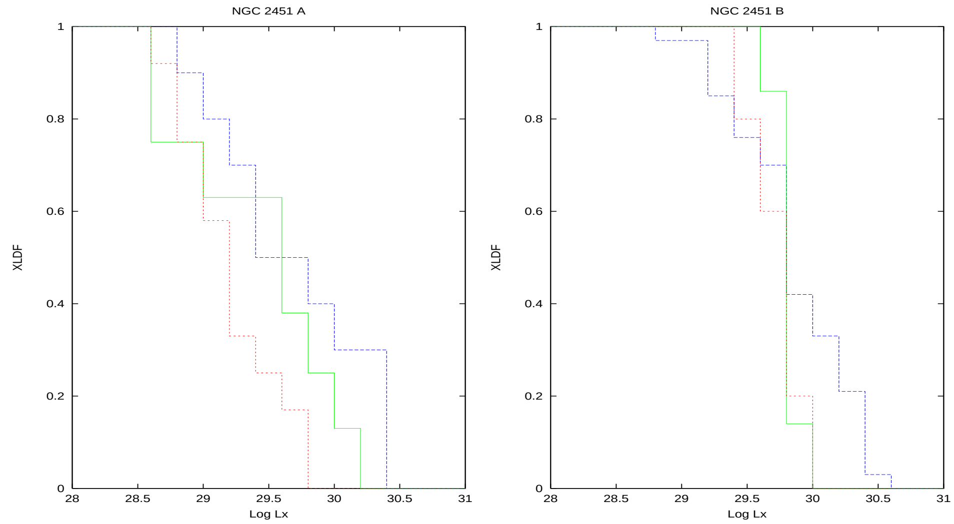

Figure 4. Cumulative X-ray luminosity distribution function of clusters NGC 2451 A (left) and B (right). The blue line indicates F- and G-stars (0.35<B–V<0.75), green: K-stars (0.75<B–V<1.25), red: M-stars (B–V>1.25). Detections only (no upper limits).

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