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ROSAT HRI survey of the open cluster Stock 2

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Abstract. We have obtained two deep HRI observations toward the open cluster Stock 2 in order to assess the X-ray luminosity level of the 112 high-probability cluster members falling in the area we have surveyed. Members have been selected on the basis of the result of a recent proper motion study based on the same photographic material and the same reduction scheme as the GSC-II project. We have reached a limiting sensitivity of $L_X \sim 3\ 10^{29}$ erg/sec for Stock 2 members and have detected 19 X-ray sources. The attained limiting sensitivity has prevented a complete sampling of the coronal emission level of Stock 2, and we have detected only three solar-type and one B9V members. We have derived the X-ray luminosity function for the Stock 2 stars in the $0.43 < (B\text{-}V)_o < 0.8$ color range and have compared it with the X-ray luminosity functions of the dG members of Praesepe, Hyades and Pleiades open clusters. While the limiting sensitivity of our observations and the present uncertainties in Stock 2 and other cluster distances do not allow to derive firm conclusion, yet, our data indicate that the coronal emission level of Stock 2 solar-type stars is more similar to that of the Hyades (or the Praesepe) than to the Pleiades one.

This in turn suggests that either Stock 2 is older than previously reported or that the current age-rotation-activity paradigm need to be revised. In this latter case Stock 2 would likely belong to the small group of open clusters (Praesepe, NGC6333 and IC 4675) for which recent X-ray surveys indicate a more complex age-rotation-activity relation than currently thought.

Key words: Galaxy: open clusters and associations: individual: Stock 2 – stars: activity – stars: late-type – X-rays: stars

1. Introduction

The study of open galactic clusters provides ideal samples of age-homogeneous solar-type (F, G and K) stars, which can be used to study the age evolution of several parameters and their inter-relationships. The better studied parameters include stellar activity (as expressed by the X-ray luminosity or by the chromospheric lines), photometric period and/or projected rotation velocity ($v \sin(i)$), and surface lithium abundance. Rotation and activity are naturally linked in the current picture in which activity is, in solar-type stars, driven by a magnetically powered dynamo.

The study of solar-type stars in the better studied nearby open clusters has been the basis on which the current picture of the evolution of stellar activity, rotation velocity, and surface lithium abundance has been built. The study of open clusters and associations with the *Einstein* observatory first and with ROSAT afterwards has shown that the mean X-ray luminosity of G, K and early M stars decreases steadily going from pre-main sequence stars (PMS) through the Pleiades ($\approx 8 \cdot 10^7$ yr), Hyades ($\approx 8 \cdot 10^8$ yr) and old disk population (eg. Barbera et al. 1993; Feigelson & Kriss 1989; Damiani et al. 1995; Micela et al. 1998, 1990, 1996; Pye et al. 1994; Stern et al. 1992, 1994, 1995; Stauffer et al. 1994).

ROSAT observations have allowed us to study the coronal emission in a large number of open clusters (cf. Jeffries 1999, for an updated review). Some of these observations have cast some doubts on the "universality" of the age-activity relation, for example, the average X-ray luminosity of G and K stars in the Praesepe appears to be much lower than in Hyades (Randich & Schmitt 1995) in spite of the Praesepe being in all aspects very similar to Hyades from the optical point of view (it is often referred to as a "Hyades twin"). The very recent observational evidence is rather confusing, since the F/G Coma Berenice cluster members have an activity level similar to the Hyades rather than Praesepe (Randich et al. 1996), whereas there are indications that coronal activity level of F/G stars of NGC 6633 (Totten et al. 1999) and F stars of IC 4756 (Randich et al. 1998) is less than the Hyades. However, in both cases, further deeper X-ray observations are clearly required to consolidate these suggestions.

Therefore the study of additional open clusters, both from the X-ray and from the optical point of view (including the determination of photometric periods), is of great importance to verify the *age-rotation-activity paradigm* (ARAP, cf. Jeffries 1999) and to determine if the Praesepe's behavior is exceptional or if indeed at any given age there is a range of activity levels or if the relation among age, rotation and activity is more complex than the ARAP.

One of the most promising open clusters, with quoted ages of 100 Myr (Piskunov 1980; Pandy et al. 1989) and 170 Myr

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(Lynga 1987), intermediate between the Hyades and Pleiades ones, is Stock 2, a rich northern cluster, discovered by J. Stock (1955) from a study of objective prism plates. Here we report on an X-ray survey of ∼ 0.5 sq.deg. in the Stock 2 central region.

The outline of the paper is the following. In Sect. 2 we summarize the status of our knowledge on the Stock 2 cluster considering also recent proper motion and photometric surveys. Sect. 3 is devoted to the presentation of the X-ray data and their analysis. In Sect. 4 we present and discuss our catalog identifications, while in Sect. 5 we discuss the X-ray activity of solar-type Stock 2 members in comparison with those of other clusters. In Sect. 6 we summarize our main conclusion. In the Appendix A we present the finding charts for the 19 X-ray sources we have detected.

2. Stock 2 properties

The nominal Stock 2 center is at $\alpha(\mathrm{J2000}) = 2\ 14\ 59$ $\delta(\mathrm{J2000}) = +59\ 13\ 57$ (Lynga 1987). The cluster has a core with an apparent diameter of about 120 arcmin, a distance of about 300 pc (Janes & Adler 1982), a mean value E(B-V) = 0.375 and variable absorption across the cluster [ΔE(B-V) = 0.12] (Krzemińsky & Serkowski 1967).

Based on DDO and UBV photometric data of two Stock 2 giants Claria et al. (1996) have found cluster metallicity [Fe/H] = -0.14 ± 0.20, i.e. compatible with being solar.

Until few years ago the only study on Stock 2 membership was the relatively old photometric study of Krzemiński & Serkowski (1967) limited only to the most luminous stars ($m_V \leq 12$). A proper motion and photometric survey complete down to m_V = 18, i.e. to early M spectral type for the nominal cluster distance, has been recently conducted in a region of ∼ 2x2 sq. deg. centered at RA=2 21 41.5 and DEC=+60 39 41 (J2000) (Lattanzi et al. 1994; Spagna 1995) and a further proper motion survey on a larger (∼ 4x6 sq. deg.) region of the sky and to a deeper magnitudes is currently in progress (Hawkins et al. 1997; Spagna et al. in preparation). These surveys are based on the same photographic material and the same reduction scheme of the GSC-II project (Mc Lean et al. 1998). In particular, the proper motions are derived following the methods described in Spagna et al. (1996). The vector point diagram (VPD) of the relative proper motions for ∼ 20000 stars brighter than V=18 within the 2x2 sq.deg. area is shown in Fig. 1. The existence and richness of the cluster centered at μ_x=0, μ_y=0 [1], as distinct from field stars, is evident. Given the available plate material and the reduction processing the mean global error on derived proper motion is $\sigma_\mu \sim 3.5$ mas/yr for $V < 16$, but increase rapidly at fainter magnitudes (Spagna 1995).

For the purpose of the present paper we have performed an analysis of only ∼ 6400 stars belonging to the 2x2 sq.deg field with a total proper motion error less than 3.5 mas/yr. We have adopted this conservative choice since our aim was to select high-probability members in order to investigate the X-ray properties of this cluster. The proper motion analysis has been performed following Jones (1997) and we retained only the stars with membership probability greater than 95%. With this criterion we end up with a list of 330 cluster members, if we had retained stars with membership probability higher than 80% we would end up with a list of 502 members. The number of cluster members indicates that Stock 2 is richer than previously thought and comparable with the Pleiades. Spagna (1995) has also computed the B, V and R colors from the plate material and a series of purposely taken BVR CCD photometry in a region of the Stock 2 (Spagna et al. 1998). Spectral types are available only for the brightest stars (Krzemińsky & Serkowski 1967).

[1] As usual in cluster membership works, proper motion were derived relative to the cluster mean velocity. Membership is not affected by the choice of the local reference frame.

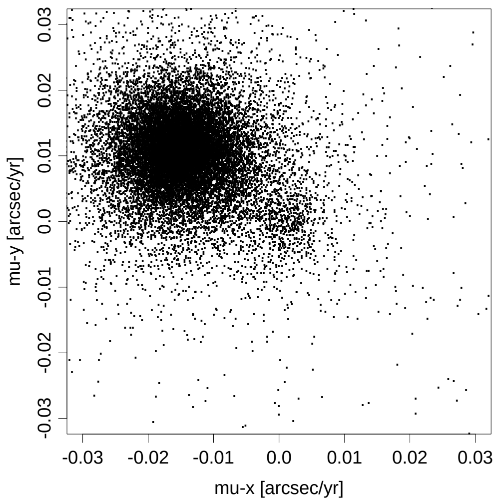

Fig. 1. VPD of relative proper motions of the stars in the ∼ 2x2 square degrees around Stock 2 center. Here, mu-x and mu-y are oriented along mu-RA and mu-DEC, respectively. The enhanced data point density at 0,0 is due to the Stock 2 cluster members.

Based on the photographically derived colors we show in Fig. 2 the color magnitude diagram (CMD) of the selected members. The CMD shows a spread of the main sequence due both to the highly variable absorption across the cluster and a (small) number of field interlopers whose contaminating percentage increases at faint magnitudes.

While this work was in progress Stock 2 has been the subject of an independent study (Foster 1997; Foster et al. 1997) aiming to find cluster members even fainter than V = 18. This study is based on the BVRI photometry from 21 5x5 sq. arcmin CCD fields covering ∼ 0.15 sq. deg. of the cluster core region and on proper motions measured from the SuperCOSMOS scans of three POSS plates in a region of ∼ 3x3 sq.deg. about the nominal cluster center. In order to identify likely cluster members Foster (1997) has retained only the stars whose positions in the (B,B-V) and (R,R-I) HR diagrams are compatible with the region bounded by the 80 and 120 Myr isocrones of D'Antona & Mazzitelli (1994), properly projected on the observational plane, with some allowance for the uncertainties in distance, reddening, photometric errors and effect of binarity. This process results in the selection of 118 candidate cluster members with $14.2 < V < 20.4$. The further screening for proper motion results in a list of 23 high probability candidate cluster mem-

Table 1. Summary of the HRI observations

Field	ROR	RA(J2000) (h m s)	DEC(J2000) ° ' "	EXPOSURE TIME (sec)	UT START DATE	UT END DATE
1	202076	2 14 21.6	+59 24 00.0	52417	28-JAN-96/10:21:22	27-FEB-96/00:15:04
2	202336	2 18 19.2	+59 45 00.0	58714	27-AUG-97/11:17:57	6-SEP-97/07:14:07

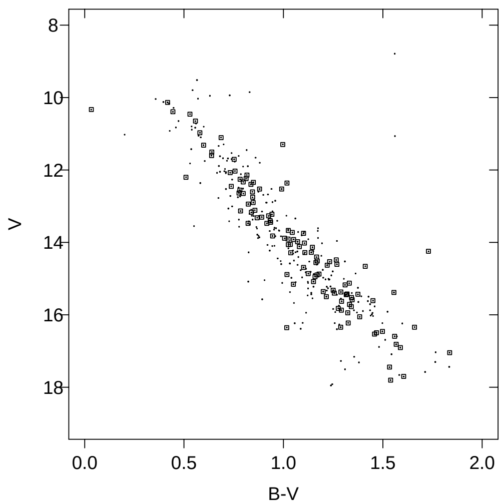

Fig. 2. Color magnitude diagram for the 330 Stock 2 members with membership probability greater than 95% and proper motion error smaller than 3.5 mas/yr. The 112 members falling in the combined field of view of the present X-ray survey are marked by squares. These latter points show the good B-V color coverage of the present survey.

bers. It is worth to stress that the selection criterion adopted by Foster strongly depends on the assumption that the age of Stock 2 is about 100 Myr. As we will see (cf. Sect. 5) our X-ray results cast some doubts on this assumption. In any case, we have also considered these stars in the following of our analysis (see below).

The analysis of the Hipparcos data has allowed to derive a new value for the Stock 2 parallax whose values is 2.90 $\pm$ 0.60 mas, resulting in a distance of 345 (+90;-59) pc (Robichon et al. 1999). The Hipparcos value is compatible with the distance of 303 pc derived from the Lynga (1987) catalog. In the following we will assume the Hipparcos derived cluster distance.

3. X-ray observations and data analysis

Assuming the observed decrease of mean X-ray luminosity with stellar age in the 100–500 Myr age range as depicted from the many clusters surveyed in X-rays (cf. Randich 1999) we would expect that the solar-type Stock 2 stars with quoted age of 1-2 10^8 yr would have a mean Log $L_X \sim 29.2$ erg/sec, corresponding to a flux $f_X \sim 1.1\ 10^{-14}$ erg sec^{-1} cm^{-2}. Since the ecliptical latitude of Stock 2 is about 57°.6, the RASS has observed the cluster for an overall exposure time of $\leq$ 0.5 ksec corresponding to a limiting sensitivity of $f_X \leq 2.4\ 10^{-13}$ erg sec^{-1} cm^{-2} largely inadequate to accomplish the objective to study the coronal emission of Stock 2 members. Hence we have requested (PI S. Sciortino) two deep (70 ksec each) HRI observations with the aim of reaching a limiting flux of $\sim 10^{-14}$ erg sec^{-1} cm^{-2}. The actual observations characteristics are summarized in Table 1.

The pointings have been selected to optimize the number and the spectral type coverage of cluster members falling in each HRI image (cf. Fig. 2). 112 high probability (> 95%) cluster members fall in the combined HRI field of view (cf. Fig. 2) with an ample spectral type coverage.

To search for X-ray sources we have adopted the wavelet transform detection algorithm developed by Damiani et al. (1997a,b) tuned for the HRI (see Micela et al. 1999 for details). The algorithm flat-fields the HRI image by using the exposure map, that takes into account the vignetted cosmic X-ray background and the intrinsic detector non-uniformities, and the particle map, that takes into account the particle-induced background that increases at large off-axis angles and contributes a substantial fraction of the total observed background. The exposure and the background maps have been built according to the prescriptions of Snowden et al. (1994) and Snowden (1998).

Since the number of photons per HRI resolution element is small, and hence the statistics is far from the gaussian limit, a large number of simulations are required to determine proper acceptance thresholds (cf. Damiani et al. 1997a). This is required since the number of spurious sources per image is a function of the exposure time. We chose the detection threshold in order to have not more than $\sim$ 1 spurious source per field, which in the case of the Stock 2 HRI images, results in a threshold corresponding approximately to a gaussian equivalent of 4.45 σ.

We have ran the algorithm on the two images finding a total of 19 X-ray sources after removing few spurious sources associated with the HRI hot spot (David et al. 1999). The two images are shown in Fig. 3, while the final source list is summarized in Table 2.

For each source we report the coordinates, the source probability of existence in equivalent σ (i.e., same probability as derived from the single-side normal integral distribution function for the reported σ), the count rate with its error, the 90% error circle according to the analytical formulation of Damiani et al. (1997a). Three sources (# 1, # 15 and # 17) have an extension that is incompatible with that of a point like source. They can be either truly extended sources or their emission can be due to few unresolved emitting objects.

Since the ROSAT HRI suffers an UV-leak (cf. David et al. 1999), whose likely origin has been only recently understood as an excess filter transmissivity mainly in the 2000–3000 Å bandpass (Barbera et al. 1997; Zombeck et al. 1997),

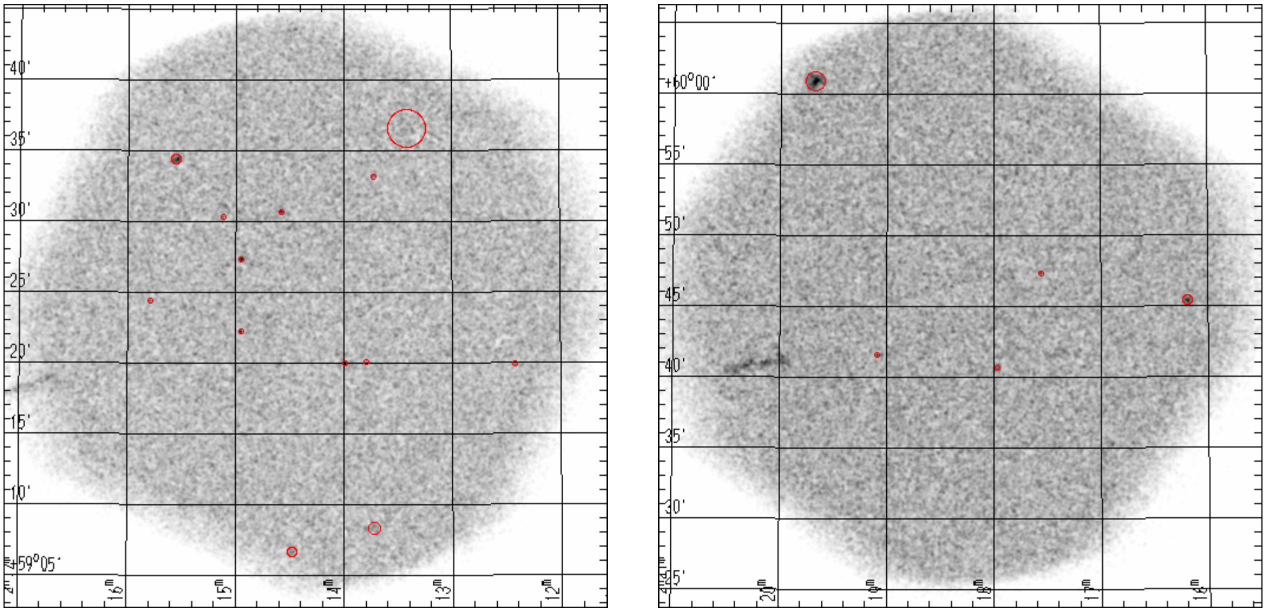

Fig. 3. HRI images of the Stock 2 central region (left) for field 1 and (right) for field 2. Data have been smoothed with a gaussian filter with a sigma of 5”. The circles represent the detections obtained as described in the text. The radius of the circles is proportional to the scale at which the source has been detected with the highest significance. For reason of clarity the two smallest radia have been increased. Note also that spurious sources, in strip like features, due to the detector hot spot have been removed.

Table 2. X-ray sources detected in the ROSAT-HRI observations

#	R.A.(J2000) (h. m. s.)	DEC.(J2000) ° ’ ”	Prob. of$^{(1)}$ Existence	Source$^{(2)}$ Extent	Rate [cnt/ksec]	Err	$r_{90\%}^{(3)}$ [”]	f_X [10^{-14} erg/cm^2/s] [0.1-2.4 keV]	Log $(L_X)^{(4)}$ [erg/sec] [0.1-2.4 keV]
1	2:12:25.6	59:19:54.3	4.46	0.42	0.68	0.23	26.6	4.76	
2	2:13:25.3	59:36:31.7	4.67	3.77	4.53	1.31	22.9	31.7	
3	2:13:43.6	59:08:17.2	4.46	1.02	1.93	0.61	30.1	13.5	30.29
4	2:13:43.8	59:33:09.7	4.86	0.64	0.45	0.15	14.4	3.15	
5	2:13:47.9	59:20:02.2	4.55	0.98	0.32	0.13	11.2	2.24	
6	2:14:00.0	59:19:57.4	9.21	1.38	1.00	0.26	10.3	7.00	
7	2:14:29.1	59:06:37.5	4.90	0.64	1.73	0.53	30.4	12.1	
8	2:14:35.4	59:30:39.9	6.50	1.18	0.66	0.20	10.8	4.62	
9	2:14:57.3	59:27:17.2	7.92	1.38	0.83	0.23	10.4	5.81	29.92
10	2:14:57.6	59:22:12.2	8.17	1.38	0.85	0.23	10.3	5.95	
11	2:15:07.6	59:30:17.0	4.52	0.62	0.32	0.12	12.9	2.24	29.51
12	2:15:33.7	59:34:21.3	10.36	1.07	2.92	0.44	14.1	20.4	
13	2:15:48.1	59:24:20.7	5.22	0.41	0.39	0.13	14.5	2.73	
14	2:16:11.8	59:45:23.6	7.58	0.75	2.12	0.54	19.3	14.8	
15	2:17:23.4	59:41:41.8	4.66	5.72	2.08	0.62	12.1	14.6	
16	2:17:34.2	59:47:17.0	5.76	0.95	0.40	0.13	10.8	2.80	
17	2:17:58.4	59:40:37.4	5.27	2.77	0.91	0.26	10.7	6.37	
18	2:19:05.8	59:41:32.0	5.44	0.86	0.36	0.13	11.1	2.52	29.56
19	2:19:40.9	60:00:50.9	18.27	1.07	15.22	3.07	18.3	106.4	

Notes

(1) Source probability of existence, expressed as the number of standard deviations of a single-side gaussian integral distribution probability.

(2) The extent is normalized to the sigma of HRI PSF according to the analytical formulation of David et al. (1999).

(3) The 90% error circle has been computed according to the analytical formulation derived by Damiani et al. (1997b), i.e. $\mathrm{r}_{90\%} = \sigma_{\mathrm{psf}} * 0.525 * \exp(5.433/\mathrm{n}_\sigma)$, where $\sigma_{\mathrm{psf}} = \mathrm{R}_{\mathrm{HP}}/\sqrt{2 * \ln(2)}$ is the width (standard deviation) of the HRI PSF with the half-power radius, R_{HP} as a function of off-axis angle is given by David et al. (1999), and n_σ is the source probability of existence reported in Column 4. Given the unexplained limitation of the ROSAT aspect reconstruction (David et al. 1999; Briel et al. 1996) we have added in quadrature a further (conservative) uncertainty of 10 arcsec to the formally derive 90% radius.

(4) We report the X-ray luminosities only for the Stock 2 members whose distance is known.

Table 3. Catalog identifications for the X-ray sources in the surveyed region

X-ray #	Name	V	B-V	V-R	Offset ["]	Sp	Membership$^{(1)}$
3		14.06	1.03	0.81	24.2	...	M (S)
6		14.54	1.06	0.84	10.5	...	NM (S)
9		14.89	1.02	0.89	9.9	...	M (S)
10		15.70	1.45	1.13	5.6	...	NM (S)
11	HD 13643	9.10	0.34	...	8.9	B9V	M (KS)
18		12.24	0.81	0.70	6.9	...	M (S)
19	HD 14173	7.19	0.97	...	10.2	G5II	NM (KS)

(1) - The membership are either based on proper-motion study in the 2x2 sq. deg. region (S), Or from the Krzemińsky & Serkowski (1967) photometric study (KS).

we have taken advantage of the limited spectral capability of the HRI (David et al. 1999) in an attempt to discriminate the true X-ray sources from those sources likely due to UV contaminating emission. These latter sources would show an HRI pulse-height spectrum with a peak in the two lowest channels. On the contrary typical X-ray sources and especially those associated with emitters toward Stock 2 seen through a non-negligeable column of interstellar matter, should show a peak in the HRI channels from 5 to 7. As a result of the analysis of the HRI spectra and taking into account the limited statistics, we have found that for sources # 1, # 4, # 10 a fraction of the observed rate (at most 10-15%) can be due to UV contaminating radiation. The effect can be present, but surely at a lower level, for source # 19. This finding confirms the true X-ray nature of the detected sources.

We have also searched the sources for variability using the Kolmogorov-Smirnov (K-S) and the Cramer-vonMises (C-vM) tests as implemented in the task "vartst" available in PROS V2.10.2. Variability with statistical significance above 99% (in both tests) has been detected for source # 11. We have verified that this variability is not an artifact of some background level temporal variation at source position.

Lacking information on each individual source, we adopted a conversion factor from observed count rate to intrinsic (i.e. not-absorbed) flux in the 0.1-2.4 keV band of 7 10^{-11} erg/cm^2/cnt assuming that the coronal X-rays of Stock 2 stars is due to an optically thin plasma emitting according to the Raymond-Smith emissivity model for a plasma temperature kT $\sim$ 0.5 keV and solar-abundances. We have also assumed that the emission is seen through an hydrogen column density with $\log(N_H) \sim 21.4$ cm^{-2}. This latter values has been derived from the mean relations A_V = 3.0 E(B-V), and N_H = 2.2 10^{21} A_V cm^{-2} (Gorenstein 1975) where for E(B-V) we have assumed the mean Stock 2 reddening. The adopted conversion factor is uncertain up to $\sim$ 40% due to individual source temperature (in the 0.3-1.3 keV range) and patchy absorption (in the $\log(N_H)$ $\sim$ 21.2-21.5 range) toward Stock 2.

For purposes of consistency, we used the same wavelet algorithm to determine upper limits to the count rates of all undetected Stock 2 members. Taking advantage of the sensitivity

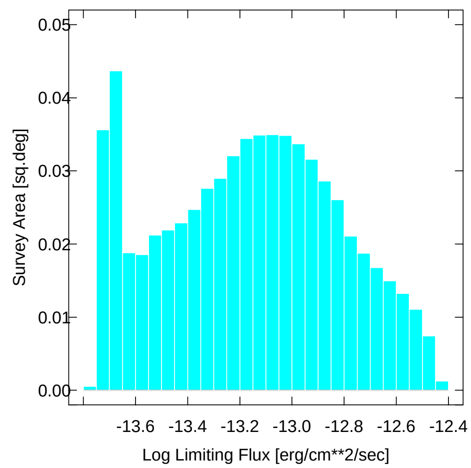

Fig. 4. The limiting sensitivity (in differential form) of our survey for a putative X-ray emitting members of Stock 2. Note that the peak at the faint side is due to the central 6 arcmin radius regions of the two HRI images. Accross this central region the PSF is very sharp and with an almost constant width. At large offaxis angles the limiting sensitivity starts to decrease as a result of the widening of the PSF-width and the effect of mirror vignetting.

maps the detection code computes we show in Fig. 4 the differential distribution of attained limiting sensitivity of the present survey for the adopted conversion factor.

4. Identifications

We have identified our detected sources by positionally matching them with the 3851 stars from the proper motion in the 2x2 sq.deg. region falling in the X-ray surveyed region regardless to their membership probability and proper motion uncertainties, furthermore we have positionally matched all the sources with SIMBAD cataloged objects. In performing these positional matches we have assumed as identification circle the 90% source positional error circle whose radius is listed in Table 2.

Using this criterion we have identified 7 out of the 19 sources with unique counterpart, 4 with cluster members and 3 with non-member stars. A summary of the result of the identification process is given in Table 3, where we report also the available optical data of the counterparts. It is worth to mention that the HRI spectra of # 11, identified with HD 13643, a B9V cluster member, does not show any evidence of UV contamination. This is not surprising since recent detailed calculation of the predicted UV contamination as a function of magnitude, spectral type and interstellar column density (Barbera et al. 2000) results in a contaminating UV rate for this star less than 8.5 10^{-6} cnt/sec. Hence, either we have found another of the rare X-ray emitting late-B/early-A stars or again we see the emission from an invisible later-type companion (cf. Panzera et al. 1999). It is worth to note that the source we have identified with a B9V star is the only one for which we have found evidence of X-ray variability.

None of the high probability low-mass members selected by Foster (1997) has been detected and we report their positions and optical data (taken from Foster 1997) and the upper-limits to their X-ray rates and fluxes (for the same conversion factor adopted before) in Table 4.

We now turn to consider the mistakenly identified X-ray detections with Stock 2 stars. This can occur when either a spurious detection or a real, but unrelated source, appears near the position of a Stock 2 star. To evaluate the probability of obtaining no mistaken identification we will make the calculation as if all the identification circles would have the same radius taken equal to 15 arcsec, i.e. the mean of the actually adopted values. Let p the ratio of the survey area (i.e. the total area of all 15" radius circles around 112 cluster members) to the total area we have surveyed with the HRI. Assuming that the spurious detections and unrelated sources appears uniformly over the field of view, p is also the probability for mistaken identification. We expect at most 2 spurious detections and at most 10 unrelated objects (see below); we will obtain no mistaken identification of a Stock 2 member, with a probability $(1 - p)^{12}$, namely the product of the probabilities to have no-mistaken identification, (1-p), for a single Stock 2 unrelated detection over the number of expected non-Stock 2 detections. Since $p \sim 8.26\ 10^{-5}$, the probability of obtaining no mistaken identification is 0.999, i.e. none of the stars identified as Stock 2 members can be due to a false identification.

4.1. Expected number of field objects

We have computed the expected number of field sources in our survey using the sensitivity maps obtained by the wavelet algorithm with a spatial resolution of 10"x10". Since Stock 2 is nearly on the galactic plane, in order to estimate the number of expected sources un-related to the cluster we have taken advantage of the results of a deep ROSAT pointed galactic plane survey (GPS; Pye et al. 1997; Sciortino et al. 1998). The derived number-flux relation has been fitted, for source count rate S > 2 PSPC cnt/ksec, as $(N > S) = N_o\, S^{-\alpha}$ with N_o = 20.6 [15.1–26.2] and α = 1.3 [0.9–1.9]. At this low latitude the expected contribution from extra-galactic object is a minor one. Using the above number-flux relation and assuming a ratio of 3.2 [2.5–3.7] between the PSPC and the HRI rates we expect about 5 [3–8] X-ray sources associated with field objects unrelated to Stock 2.

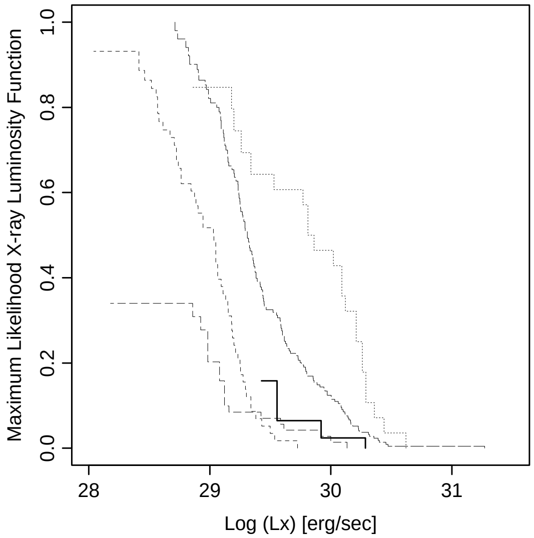

Fig. 5. The maximum likelihood X-ray luminosity function of Stock 2 solar-type dwarf members (solid line) compared with the analogous luminosity functions (from left to right) for the Praesepe (long-dashed line), the Hyades (dashed line), the Pleiades (long-dashed line) and α Per (dotted-line).

Their number can increase up to a maximum of 10 if we assume the HRI being only 2.5 times less sensible than the PSPC. In summary, their number is in agreement with the actual number of X-ray sources without a Stock 2 counterparts.

5. X-ray activity of solar-like stars of Stock 2

Unfortunately the attained limiting sensitivity is not deep enough to detect a sizeable number of Stock 2 members, anyway it is worth noticing that 3 of the 4 detected cluster members have intrinsic $(B-V)_o$ color – i.e. after the mean reddening correction E(B-V) = 0.375 is applied – that are compatible with those of dwarfs of spectral type $\sim$ F6V-K0V ($0.43 \leq (B-V)_o \leq 0.8$). For the other 46 undetected Stock 2 members in this color range we have report the available optical data and the upper limits to their X-ray counts rates and luminosities in Table 5.

Using the Kaplan-Maier estimator (cf. Feigelson & Nelson 1985) and taking advantage of the X-ray luminosities values (3) and upper-limits (46) we have built the maximum likelihood X-ray luminosity distribution function (XLF) for the dG-type Stock 2 members. The derived XLF is shown in Fig. 5 where for comparison we have also included the XLF's for the Praesepe (Randich & Schmitt 1995), the Hyades (Stern et al. 1995), the Pleiades (Micela et al. 1996, 1999; Stauffer et al. 1994) and α Per (Randich et al. 1996). In the case of Praesepe the X-ray luminosity values have been recomputed for the Hipparcos distance of 180 pc versus the traditionally adopted distance of 165 pc. While it is clear that deeper X-ray observations are needed for a better determination of the X-ray luminosity level of Stock 2 solar-type stars, yet the available data suggest that Stock 2 dG-type members have X-ray luminosity level lower than the Pleiades (or other younger stars) and more compatible with the X-ray emission level of

Table 4. Optical photometry and upper-limits of X-ray count rates, fluxes and luminosities for other possible members from Foster (1997)

R.A.(J2000) (h. m. s.)	DEC.(J2000) ◦ ' "	V	B-V	V-R	Rate [cnt/ksec]	f_X [10^{-14} erg/cm^2/s] [0.1-2.4 keV]	Log(L_X) [erg/sec] [0.1-2.4 keV]
2:13:37.0	59:22:54.5	15.17	1.40	0.80	< 0.29	< 2.03	< 29.46
2:13:44.8	59:20:09.2	18.93	1.81	1.26	< 0.30	< 2.10	< 29.66
2:13:45.0	59:20:43.9	16.55	1.61	0.93	< 0.30	< 2.10	< 29.46
2:13:45.0	59:20:44.0	16.59	1.60	0.98	< 0.30	< 2.10	< 30.01
2:13:47.0	59:31:37.2	18.48	1.83	1.37	< 0.44	< 3.08	< 30.00
2:13:55.3	59:22:18.1	19.08	1.87	1.28	< 0.28	< 1.96	< 30.19
2:14:06.1	59:21:31.1	17.57	1.78	1.04	< 0.28	< 1.96	< 29.74
2:14:10.6	59:23:40.5	17.16	1.79	1.07	< 0.29	< 2.03	< 29.46
2:14:12.1	59:30:22.1	16.38	1.65	0.94	< 0.32	< 2.24	< 29.51
2:14:19.7	59:23:57.6	19.30	1.91	1.16	< 0.30	< 2.10	< 30.26
2:14:23.8	59:15:37.2	18.26	1.80	1.28	< 0.43	< 3.01	< 29.68
2:14:24.8	59:25:39.1	14.28	1.30	0.61	< 0.29	< 2.03	< 29.48
2:14:38.7	59:22:16.3	15.73	1.42	0.73	< 0.29	< 2.03	< 29.48
2:14:58.1	59:16:08.1	16.49	1.56	0.97	< 0.48	< 3.36	< 29.50
2:15:01.2	59:08:25.1	16.46	1.75	1.13	< 1.81	< 12.7	< 29.46
2:15:04.2	59:15:43.3	15.46	1.54	0.80	< 0.55	< 3.85	< 29.50
2:15:06.7	59:22:37.9	16.70	1.71	0.85	< 0.31	< 2.17	< 29.45
2:15:09.7	59:19:19.3	17.95	1.87	1.25	< 0.38	< 2.66	< 29.58
2:15:13.9	59:23:51.6	17.27	1.78	0.89	< 0.32	< 2.24	< 29.63
2:15:15.0	59:18:51.5	14.69	1.20	0.73	< 0.45	< 3.15	< 29.65
2:15:46.3	59:15:25.0	15.23	1.26	0.71	< 1.02	< 7.14	< 29.47
2:15:55.4	59:17:45.5	15.26	1.40	0.81	< 0.99	< 6.93	< 29.45
2:16:01.5	59:14:06.9	15.41	1.43	0.82	< 1.54	< 10.8	< 29.48

These possible members have been selected by Foster (1997) who has derived and listed their positions, magnitudes and colors.

the Hyades members. Based on the published Stock 2 age (100-170 Myrs) and on the X-ray activity-age relation found by the estensive *Einstein* and ROSAT open cluster surveys (cf. Jeffries 1999) we would instead expect that Stock 2 coronal emission would be similar to that of the Pleiades. In order to put this statement on more solid basis we have compared the values of the X-ray luminosities (both detection and upper limits) for the dG Stock 2 sample with the analogous samples of the Hyades and the Praesepe. Since our data are censored, i.e. they contain a large number of upper-limits, we have adopted the non-parametric two sample Gehan test that is more sensitive at the uncensored end (cf. Feigelson & Nelson 1985), i.e. it is more prone to find differences among the X-ray luminosity levels of detected sources. The Stock 2-Praesepe comparison results in the two samples being indistinguishable (the confidence level for rejecting the null hypothesis that the two samples are drawn from the same parent population is 44%), in the case of the Stock 2-Hyades comparison we obtain a confidence level of 65%, i.e. the two samples are again indistinguishable. The Stock 2-Pleiades comparison results in confidence level of 90% suggesting that Stock 2 and the Pleiades dG stars have different X-ray luminosity levels.

Since the somewhat large uncertainties on the adopted Stock 2 distance could affect the derived X-ray luminosities we have repeated the Stock 2-Pleiades comparison adopting the largest Stock 2 distance, i.e. 335 pc, compatible with Hipparcos results, in this case the Stock 2 and the Pleiades cannot be statistically distinguished (confidence level 49%), on the contrary assuming the smallest admissible Stock 2 distance (286 pc) results in Stock 2 and the Pleiades being clearly distinct (confidence level 99.2%).

Finally we note that we have not detected any of the 23 faint Stock 2 putative members reported by Foster (1997) and selected on the basis of their positions on the CMD diagram for a Stock 2 age of $\sim$ 100 Myr. Assuming the mean extinction correction (E(B-V)=0.375) we have subdivided those 23 putative members in 14 dK ($0.8 <$ (B-V)$_o$ ≤ 1.4) and 9 dM ((B-V)$_o$ > 1.4) none of which emits, at the nominal Stock 2 distance, above Log(L_X) $\sim$ 29.5 erg/sec (cf. Table 4). In the case of the Pleiades the medians and the 10-90% quantiles of Log(L_X) (in erg/sec) are 29.21 [29.7,28.8] and 28.85 [28.65,29.35] for the dK and dM stars, respectively; hence the lack of any single detection among the 14 dK putative members is hard to explain on pure statistical basis and we argue that either most of those 23 stars are not Stock 2 members, likely because Stock 2 age is quite different than the value of 100 Myr adopted by Foster (1997), or, again, that the coronal emission level of Stock 2 dK members is lower than that of the Pleiades. In this latter case Stock 2 would be another exception to the ARAP.

In summary, available data suggests that the X-ray luminosity level of Stock 2 dG and dK members is lower than that of the Pleiades members of corresponding spectral types. Avail-

Table 5. Optical photometry and upper-limits to X-ray count rates, fluxes and luminosities for the undetected solar-like Stock 2 members

R.A.(J2000) (h. m. s.)	DEC.(J2000) ○ ’ ”	V	B-V	V-R	Rate [cnt/ksec]	f_X [10^{-14} erg sec^{-1} cm^{-2} [0.1-2.4 keV]	Log(L_X) [erg/sec] [0.1-2.4 keV]
2:12:36.3	59:28:22.9	16.353	1.017	0.819	$<$ 1.09	$<$ 7.6	$<$ 30.04
2:13:02.4	59:31:07.9	14.136	1.146	0.93	$<$ 0.82	$<$ 5.8	$<$ 29.91
2:13:23.1	59:22:52.9	14.407	1.167	0.915	$<$ 0.37	$<$ 2.6	$<$ 29.57
2:13:25.8	59:21:30.3	15.156	1.05	0.854	$<$ 0.35	$<$ 2.5	$<$ 29.54
2:13:27.2	59:22:32.2	14.288	1.037	0.81	$<$ 0.34	$<$ 2.4	$<$ 29.53
2:13:45.1	59:06:22.8	14.897	1.169	0.876	$<$ 2.72	$<$ 19.0	$<$ 30.43
2:13:45.1	59:08:26.5	14.06	1.025	0.811	$<$ 1.93	$<$ 13.5	$<$ 30.29
2:13:46.5	59:34:54.8	14.864	1.125	0.893	$<$ 0.74	$<$ 5.2	$<$ 29.87
2:13:49.2	59:27:00.4	13.226	0.942	0.76	$<$ 0.28	$<$ 2.0	$<$ 29.45
2:13:50.6	59:38:21.0	11.295	0.997	0.807	$<$ 1.19	$<$ 8.3	$<$ 30.08
2:14:00.2	59:11:32.2	14.021	1.106	0.842	$<$ 0.93	$<$ 6.5	$<$ 29.97
2:14:01.6	59:11:32.2	13.269	0.925	0.738	$<$ 0.93	$<$ 6.5	$<$ 29.97
2:14:07.1	59:35:36.0	13.749	1.101	0.819	$<$ 0.74	$<$ 5.1	$<$ 29.87
2:14:19.5	59:19:47.2	13.724	1.045	0.823	$<$ 0.28	$<$ 2.0	$<$ 29.45
2:14:19.5	59:32:30.4	13.981	1.071	0.802	$<$ 0.44	$<$ 3.0	$<$ 29.64
2:14:34.6	59:18:45.3	12.755	0.845	0.673	$<$ 0.28	$<$ 2.0	$<$ 29.45
2:14:37.3	59:16:20.9	14.559	1.163	0.881	$<$ 0.4	$<$ 2.8	$<$ 29.61
2:14:49.7	59:22:11.6	13.111	0.856	0.715	$<$ 0.3	$<$ 2.1	$<$ 29.47
2:14:58.0	59:27:21.0	14.885	1.018	0.886	$<$ 0.83	$<$ 5.8	$<$ 29.92
2:15:14.5	59:18:45.3	14.691	1.101	0.808	$<$ 0.46	$<$ 3.2	$<$ 29.66
2:15:40.6	59:11:32.2	12.525	0.991	0.824	$<$ 1.5	$<$ 10.5	$<$ 30.18
2:15:46.1	59:36:58.5	12.526	0.88	0.695	$<$ 1.63	$<$ 11.4	$<$ 30.21
2:15:54.3	59:52:06.1	12.139	0.816	0.632	$<$ 3.85	$<$ 27.0	$<$ 30.59
2:16:04.0	59:12:13.4	12.362	1.018	0.848	$<$ 2.33	$<$ 16.3	$<$ 30.37
2:16:09.5	59:27:21.0	13.919	1.051	0.806	$<$ 1.06	$<$ 7.5	$<$ 30.03
2:16:12.2	59:55:53.0	13.672	1.024	0.77	$<$ 4.63	$<$ 32.4	$<$ 30.67
2:16:21.8	59:27:41.6	14.114	1.08	0.788	$<$ 1.38	$<$ 9.6	$<$ 30.14
2:16:34.2	59:24:36.0	13.301	0.891	0.722	$<$ 1.72	$<$ 12.1	$<$ 30.24
2:16:45.2	59:22:32.2	14.946	1.159	0.88	$<$ 2.53	$<$ 17.7	$<$ 30.40
2:16:50.7	59:43:30.4	14.279	1.108	0.831	$<$ 0.67	$<$ 4.7	$<$ 29.82
2:17:03.1	59:36:37.9	14.513	1.17	0.843	$<$ 0.83	$<$ 5.8	$<$ 29.92
2:17:27.8	59:31:28.5	12.899	0.848	0.689	$<$ 1.17	$<$ 8.2	$<$ 30.07
2:17:48.5	59:42:49.2	13.906	1.023	0.813	$<$ 0.27	$<$ 1.9	$<$ 29.43
2:18:02.2	60:02:24.9	14.053	1.034	0.801	$<$ 2.06	$<$ 14.4	$<$ 30.31
2:18:07.7	59:26:39.7	12.941	0.823	0.714	$<$ 2.29	$<$ 16.1	$<$ 30.36
2:18:09.1	59:35:36.0	13.886	1.006	0.795	$<$ 0.49	$<$ 3.5	$<$ 29.69
2:18:09.1	59:46:56.7	13.473	0.917	0.712	$<$ 0.28	$<$ 2.0	$<$ 29.44
2:18:25.6	59:55:11.7	14.275	1.14	0.888	$<$ 0.59	$<$ 4.1	$<$ 29.77
2:18:27.0	59:27:21.0	15.082	1.151	0.883	$<$ 2.01	$<$ 14.1	$<$ 30.30
2:18:32.5	59:53:49.2	12.344	0.849	0.706	$<$ 0.46	$<$ 3.2	$<$ 29.67
2:18:38.0	59:42:07.9	13.32	0.868	0.678	$<$ 0.28	$<$ 2.0	$<$ 29.45
2:19:05.5	59:41:26.7	12.241	0.812	0.702	$<$ 0.36	$<$ 2.5	$<$ 29.56
2:19:08.2	60:00:21.1	13.476	0.822	0.671	$<$ 1.73	$<$ 12.1	$<$ 30.24
2:19:31.6	59:49:21.1	13.401	0.933	0.757	$<$ 0.53	$<$ 3.7	$<$ 29.73
2:19:42.6	59:34:34.2	13.824	0.945	0.739	$<$ 1.16	$<$ 8.1	$<$ 30.06
2:20:08.7	59:52:26.7	13.445	0.936	0.718	$<$ 1.45	$<$ 10.1	$<$ 30.16

able data do not allow to assess if the X-ray luminosity level of Stock 2 members is indeed more similar to the Praesepe members than to the Hyades ones. Our limited X-ray sensitivity and the present uncertainty on Stock 2 distance unfortunately do not allow us to draw more firm conclusions.

6. Summary and conclusion

Taking advantage on the recent availability of a proper motion survey (Spagna 1995) we have selected 303 high probability Stock 2 members out of $\sim$ 20000 stars. We have surveyed with two medium-deep ROSAT HRI exposures ($\sim$ 55 ks each) 112 Stock 2 members with an ample coverage of spectral types. Our survey reaches $L_X \sim 3\ 10^{29}$ erg/sec at the cluster distance of 345 pc. We have detected 19 X-ray sources, seven of which have a catalogued stellar counterparts. Out of these 7 stars four are Stock 2 members, and in particular three have B-V color in the expected range of $\sim$ dG cluster members stars. For all the undetected Stock 2 members and in particular for 46 solar-type stars we have consistently derived upper-limits to the emitted X-ray rates

The limited sensitivity of our X-ray survey has allowed us just to sample the tail of the X-ray luminosity functions of Stock 2 solar-like stars, yet, the comparison of the derived luminosity function with those of other open clusters suggests that the Stock 2 solar-like stars have a coronal emission level more similar to the Hyades or the Praesepe ones than that of the Pleiades. Moreover the lack of X-ray emission above Log (L_X) $\sim$ 29.5 erg/sec from 23 fainter possible members – mostly with B-V color of dK stars – selected by Foster (1997) from their positions on a CCD-derived CMD is hard to reconcile with the know X-ray luminosity of Pleaides dK members. Since the number of X-ray sources unrelated to Stock 2 members is in good agreement with the number predicted on the basis of the log N - log S of field objects, we have additional evidence that the unidentified X-ray sources are unlikely to be related to unknown Stock 2 members emitting above the X-ray limiting sensitivity of the present survey. The available evidence indicates that the Stock 2 cluster is older than $\sim$ 100-170 Myr, the age usually reported for this cluster. Alternatively, if the quoted age of Stock 2 is indeed correct, our findings would indicate that Stock 2 is another exception to the ARAP.

This is an important issue since the recent studies of NGC6633 (Totten et al. 1999) and IC 4756 (Randich et al. 1998) have shed some doubts on the activity level of one cluster being indeed representative of all clusters of the same age. However, even for the very clear case of Praesepe, we have not a convincing explanation of the observational evidence. The observational evidence for the Praesepe, as well as for NCG 6633, IC 4756, and now for Stock 2 – if we trust its quoted age of 100-170 Myr – indicates that age/rotation and spectral-type (or mass) alone do not seem to explain or determine the X-ray activity level suggesting that some additional parameter is needed. This parameter is likely related to properties of the internal stellar structure and their effect on the efficiency of stellar dynamos (cf. Micela et al. 1996).

Our X-ray data do not allow us to asses if activity level in Stock 2 is more similar to the Hyades one than to the even lower activity level found in the Praesepe. Future, more deeper observations with CHANDRA or XMM will likely address this issue. Furthermore, since in the age range from 100 Myr (Pleiades) to the 700 Myr (Hyades) the lithium is indeed a powerful discriminator of age, we envisage that future high resolution lithium observations will allow to settle the question of the Stock 2 age that the present X-ray survey has opened.

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Appendix A: sources without cataloged counterpart and finding charts

We have detected 12 sources without cataloged counterparts. In order to ease the identification work we have produced for the X-ray sources the finding charts based on the STScI Digitized Sky Survey CD-ROMs. Each finding chart is a square of 2' of size. The circles inside the finding charts represent the 90% error circle. The finding charts are shown in Fig. A.1 for reader convenience. Their inspection reveals that most of the sources without catalogued counterparts have a quite faint object within respective error circle.

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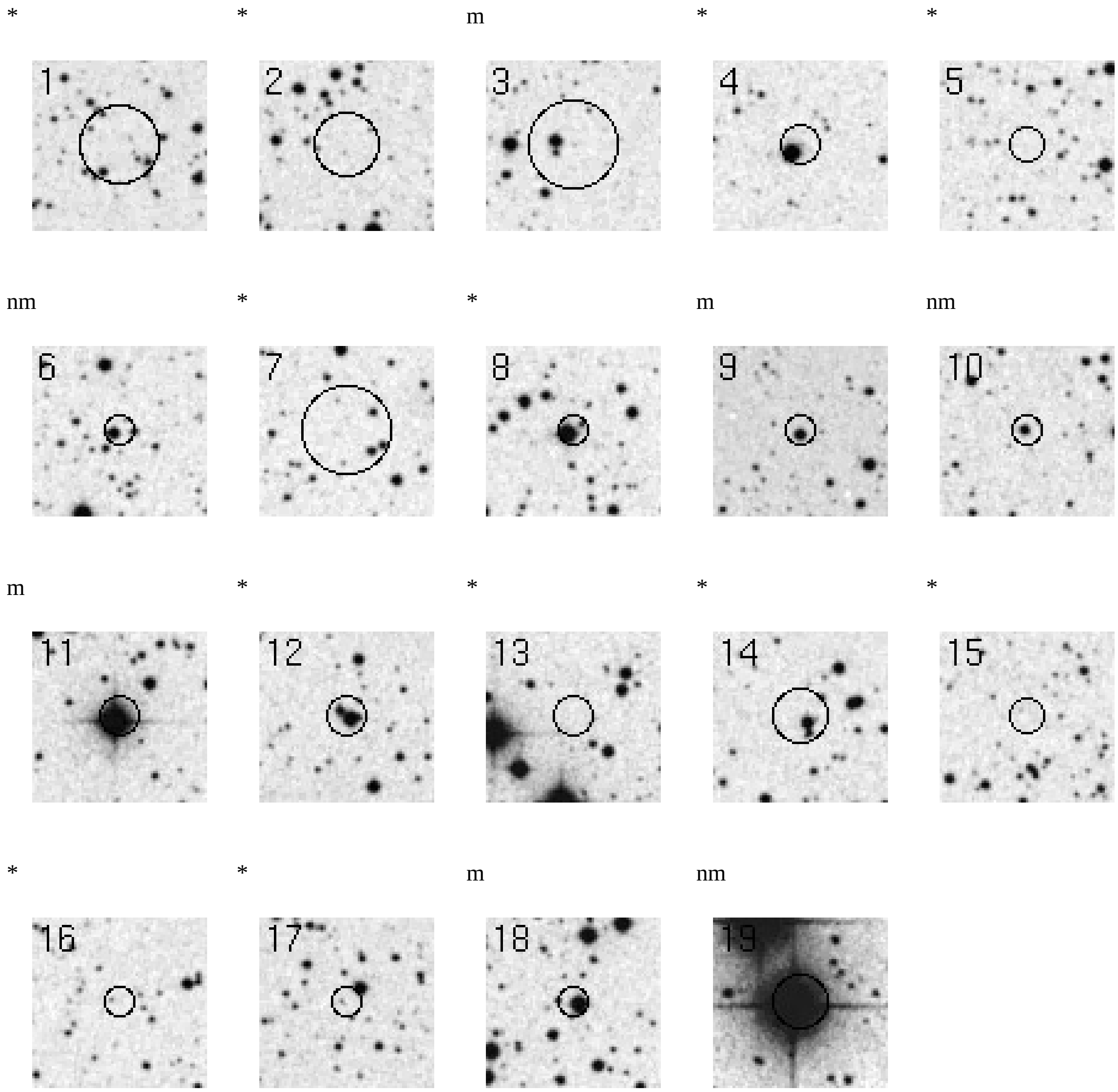

Fig. A.1. Finding charts for the 19 HRI sources detected in the Stock 2 region, extracted from the STScI DSS, with overlaid the 90% confidence positional error circle. Each chart is 2' on a side. An asterisk on the upper left corner marks those sources for which no catalog identification has been found. A *m* (member) or a *nm* (non-member) indicate the membership status of catalogued counterparts.

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