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2MASS galaxies in the Fornax cluster spectroscopic survey⋆ *(Research Note)*

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ABSTRACT

Context. The Fornax cluster spectroscopic survey (FCSS) is an all-object survey of a region around the Fornax cluster of galaxies undertaken using the 2dF multi-object spectrograph on the Anglo-Australian telescope. Its aim was to obtain spectra for a complete sample of all objects with $16.5 < b_j < 19.7$ irrespective of their morphology (i.e. including "stars", "galaxies" and "merged" images).
Aims. We explore the extent to which (nearby) cluster galaxies are present in 2MASS. We consider the reasons for the omission of 2MASS galaxies from the FCSS and vice versa.
Methods. We consider the intersection (2.9 square degrees on the sky) of our data set with the infra-red 2 micron all-sky survey (2MASS), using both the 2MASS extended source catalogue (XSC) and the point source catalogue (PSC). We match all the XSC objects to FCSS counterparts by position and also extract a sample of galaxies, selected by their FCSS redshifts, from the PSC.
Results. We confirm that all 114 XSC objects in the overlap sample are galaxies, on the basis of their FCSS velocities. A total of 23 Fornax cluster galaxies appear in the matched data, while, as expected, the remainder of the sample lie at redshifts out to $z = 0.2$ (the spectra show that 61% are early type galaxies, 18% are intermediate types and 21% are strongly star forming).The PSC sample turns out to contain twice as many galaxies as does the XSC. However, only one of these 225 galaxies is a (dwarf) cluster member. On the other hand, galaxies which are unresolved in the 2MASS data (though almost all are resolved in the optical) amount to 71% of the non-cluster galaxies with 2MASS detections and have redshifts out to $z = 0.32$.

Key words. surveys – galaxies: statistics – galaxies: clusters: individual: Fornax

1. Introduction

There are obvious differences between infra-red and optically selected catalogues of galaxies. In this note we discuss the results obtained by cross-referencing objects in our "all-object" Fornax Cluster Spectroscopic Survey (FCSS: Drinkwater et al. 2000b) with those in the infra-red 2 Micron All-Sky Survey (2MASS: Jarrett et al. 2000) in the direction of the Fornax cluster. Brief details of these surveys are presented in Sect. 2. At first glance, these two catalogues are poorly matched, in that 2MASS is a much larger area but comparatively shallow survey, relative to the FCSS. However, the FCSS is designed to cover *all* types of object within its magnitude range, so a wide range of objects may inhabit the overlap in parameter space. Many of the objects in common are stars, but we will concentrate here on the galaxy component, and especially on the cluster members. Cole et al. (2001, henceforth C2001), have previously matched 2MASS to the general 2dF Galaxy Redshift Survey (2dFGRS: Colless et al. 2001). However, here we consider the 2MASS XSC objects which would not have had 2dFGRS counterparts and the galaxy content of the unresolved sources in the PSC.

2. The catalogues

The 2dF multi-fibre spectrograph (Lewis et al. 2002) on the Anglo-Australian Telescope, provides the opportunity to make truly complete spectroscopic surveys of a given area on the sky, down to well determined, faint limits, irrespective of target type. The FCSS exploited this by fully surveying a region centred on the Fornax Cluster of galaxies (Drinkwater et al. 2000b,a).

In common with the main 2dFGRS (which did not cover the Fornax area), our input catalogue for the FCSS comes from UKST Sky Survey plates digitised by the APM machine (Irwin et al. 1994), but unlike other surveys, we avoid any morphological pre-selection and include *all* objects, both resolved and unresolved (i.e. "stars" and "galaxies") between our sample limits at $16.5 \leq b_j \leq 19.7$, as well as the confused sources classified as "merged". We report results here from the central 2 degree

⋆ Our matched catalogues are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via
http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/476/59

diameter field from the FCSS (centred close to the first ranked cluster galaxy NGC 1399) for which the redshift measurements are 92% complete (Deady et al. 2002). In order to obtain a greater overlap with 2MASS, we have also added in the galaxies brighter than $b_j = 16.5$ in our survey area by utilising our companion survey (Drinkwater et al. 2001b) which used the FLAIR spectrograph on the UK Schmidt Telescope, as well as literature sources. Note that these were morphologically selected as galaxies but we do not expect any confusion of compact galaxies with stars at these very bright magnitudes.

The 2MASS[1] Second Incremental Data Release (March 2000) (also used by C2001) includes both a Point Source Catalogue (PSC) and an Extended Source Catalogue (XSC). The XSC should be be complete for all galaxies brighter than $K_s = 13.5$ and contains objects down to $K_s \simeq 14.4$, depending on their degree of extension, surface brightness etc. Given the resolution of 2MASS, XSC objects are typically in excess of 10″ in diameter (Jarrett et al. 2000). For the photometry below we used the extrapolated 'total" magnitudes.

The FCSS area was used to define our potential sky coverage, viz. a 2° diameter circle centred at $03^h38^m29^s$, $-35°27'$ (J2000). We used the "Gator" query tool in the IPAC IRSA web interface to extract sources from the 2MASS PSC and XSC satisfying the same area constraint. In fact, Fornax lies close to the edge of the region surveyed for the 2MASS Second Incremental Data Release, so the overlap region is slightly less than the nominal 2dF area and covers 2.9 square degrees, containing 3204 FCSS objects, of which the great majority are Galactic stars or galaxies behind the cluster. In reprocessing data for the later All Sky Data Release, several former PSC objects were reclassified into the XSC. In what follows we have used this updated information but retained our original field area limit[2].

A generous search radius of 3″ was used in matching 2MASS to FCSS objects although it is already known that for point sources 2MASS positions agree with those from the APM catalogue to ∼0.5″. The relatively large search radius of 3″ was retained to allow matching of large, possibly irregular, galaxies with larger centroid uncertainties. A significant contribution to the difference in object centroids between 2MASS and APM will be variations in colour for large irregular galaxies. In total 114 XSC and 2021 PSC objects (not also in the XSC) match with ones in the FCSS or the brighter sample. Our matched catalogues are available from the CDS in electronic form.

3. 2MASS XSC objects

Of the 114 2MASS XSC objects in the area, 84 are matched in the FCSS itself, 28 are in the brighter FLAIR sample and two are 15th magnitude galaxies in the Ferguson (1989) Fornax Cluster Catalogue (FCC). All are confirmed as galaxies, with redshifts showing them to be in or behind the Fornax Cluster. This compares with ∼11% of XSC objects not matched in the 2dFGRS in C2001. In our area there are no saturated or multiple stars in the XSC and none wrongly classed as stars by APM, while 4 were erroneously classed as extended in the original XSC – consistent with the combined tally of ∼7% in C2001 – but the latter 4 were removed in the next release. The remaining ∼4% of unmatched 2MASS objects in C2001 were "merged" images in the *r* band APM images, whereas we spectroscopically observed all of these. (In fact, in our area we have a surprisingly large number of merged images, amounting to ∼22% of the 2MASS sample).

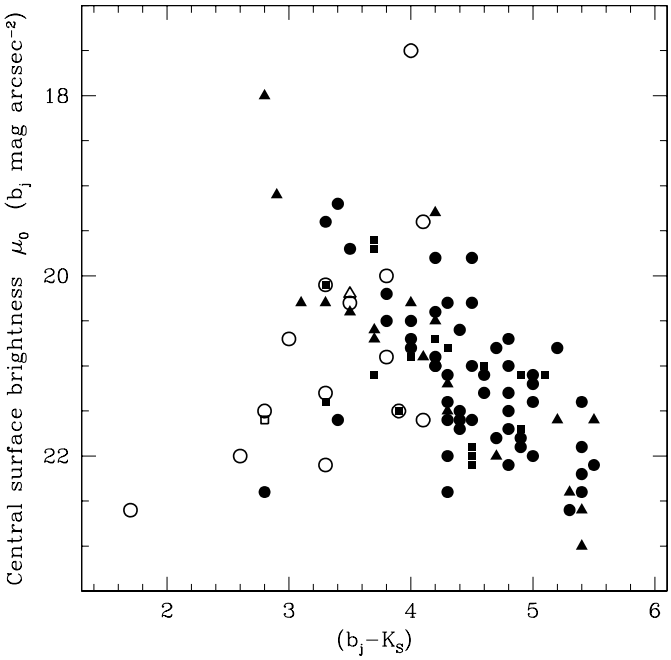

Fig. 1. Central surface brightness versus $b_j - K_s$ colour for matched XSC objects. Open (filled) circles are cluster (background) early types, squares intermediate types and triangles late types.

Given the range of colours seen for the galaxies (up to $b_j - K_s \simeq 5.5$), one would expect the FCSS to be deep enough in magnitude to pick up all the genuinely extended 2MASS sources in the complete sample to $K_s = 13.5$, as was found by C2001 for the comparably deep 2dFGRS. It is just possible for objects in the faint tail down to $K_s \simeq 14.4$ to be missed by the FCSS if they were also of the very reddest colours $b_j - K_s \simeq 5.4$, but as we have seen there are no examples of this in our sample.

A total of 23 cluster galaxies ($cz \simeq 1400 \pm 800$ km s^{-1}) appear in the matched data. All bar one is an early type according to the types assigned in Drinkwater et al. (2001b), the FCSS or NED. Note that only 2 of the cluster objects are from the actual 2MASS/FCSS paired data, and one of those was only included because of an erroneous input magnitude, as it is actually significantly brighter than the FCSS bright limit. All the rest are from the brighter spectroscopic surveys. Thus genuine cluster dwarfs, as sampled by the FCSS, are virtually absent from the 2MASS XSC, despite having exactly the same b_j magnitudes as detected background galaxies. This is a result of a combination of the cluster dwarfs" blue colours and, especially, low surface brightnesses (Monnier Ragaigne et al. 2003).

Matching to various template spectra, of the 83 FCSS galaxies (i.e. counting the interacting pair only once), 50 (61%) have the classic K star-like spectrum of an early type galaxy (Morgan & Mayall 1957), 18% match F or G star spectra (intermediate type) and 21% are emission line galaxies (late types). These are extremely similar to the fractions obtained by C2001 – 62% early type, 22% Sa-Sb, 16% late type – on the basis of a completely independent spectral typing using a principal component analysis (see Madgwick et al. 2002). The types match reasonably well to the galaxies' $b_j - K_s$ colours, though there exist a

[1] 2MASS is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/ California Institute of Technology. Funding for the survey has been provided by NASA and the NSF.

[2] Strictly speaking, 6 objects were reclassified *out* of the XSC in the all sky 2MASS catalogue, but as we confirm that they really are galaxies, we have retained them in the "extended' sample. They make no significant difference to any of the statistics presented later.

few late types with red colours and the cluster dwarfs have rather blue colours compared to Poggianti (1997) models (see Fig. 1). The bluest colours are found amongst the low surface brightness cluster members (cf. Bell et al. 2003)[3].

There are also some low surface brightness but very red objects, several of which are clearly edge-on spirals from their images, in agreement with their spectral typing. Otherwise, the overall trend for decreasing surface brightness with redder colour is as expected from the combined effect of the *k*-correction reddening and the cosmological dimming of surface brightness with redshift for the dominant early type background galaxy population. (The redshift range is more extended than that shown by C2001, as they limited their sample at $K_s = 13.2$; we can also note that the galaxies that would have been missed by 2dFGRS selection have the same redshift range as the others).

4. 2MASS PSC objects

Now consider any "small" galaxies hidden among the 2MASS Point Source Catalogue (PSC) objects. These may be, of course, merely distant rather than physically small. Finlator et al. (2000), in a study of stars detected in 2MASS, have previously noted (but not discussed further) the fact that ≈15% of PSC objects correspond to resolved images in the Sloan Digital Sky Survey (SDSS) commissioning data.

In all there are 2021 matches of 2MASS point sources with FCSS objects out of a total of 3204 objects (both optically resolved and unresolved) in the FCSS catalogue in the overlap region. This region contains 3982 PSC objects which are not already covered by the XSC. Thus only just over half (51%) have FCSS counterparts. Given the expected stellar number counts, a substantial number of unmatched PSC objects will be stars brighter than $b_j = 16.5$. From the Bahcall & Soneira (1980) models, we expect around 1200 stars brighter than the FCSS bright limit in a 3 square degree area at $b \sim -50^o$. The PSC contains significantly fainter sources than does the XSC, down to $K_s \simeq 15.5$ (with a few even fainter), so given the very broad range of colours exhibited by both stars and galaxies (Bessell & Brett 1988, C2001), many of the fainter 2MASS PSC sources will be red enough to fall off the *faint* end of the FCSS sample. Clearly anything fainter than $K_s \sim 15$ and/or redder than $b_j - K_s \sim 4.5$ is likely to be lost. Going the other way, a smaller fraction (36%) of FCSS objects do not have 2MASS counterparts. As 2MASS has no bright limit, these must be lost because they are too faint in the IR (i.e. too blue in optical to IR colour).

After removing galaxies also present in the XSC we are left with 228 PSC objects (including 3 QSOs) which have FCSS redshifts showing them to be extragalactic ($cz > 900$ km s^{-1}), i.e. twice as many galaxies as are found in the XSC. As a minimum, 6% (228/3982) of PSC objects must be extragalactic (11% of matched PSC/FCSS objects). This is rather lower than the ≈15% of PSC objects found to be resolved in SDSS by Finlator et al. (2000). Unmatched PSC objects may include fainter, but still resolved, galaxies; almost all the PSC/FCSS objects have $b_j \geq 18.2$ and most have $18.7 \leq b_j \leq 19.7$.

The 225 PSC galaxies (Fig. 2) again contain a substantial number classified as "merged" (36 in the b_j band, though only 13 in r_f) and 2 which are optically unresolved (one is an ultra-compact dwarf (UCD) from Phillipps et al. 2001; and the other a compact emission line galaxy from Drinkwater et al. 1999). Both merged and unresolved objects would typically be ignored in galaxy redshift surveys. The matched sample has a median z of 0.16, essentially the same as that of the whole FCSS galaxy sample, and reaches $z = 0.32$. However, with many fewer objects over the same redshift range, the matched sample is obviously picking out only the physically more luminous, redder, and presumably more massive, galaxies. 2MASS misses just as large a fraction (or even a larger fraction) of the nearby FCSS galaxies as distant ones. Indeed, just one cluster galaxy is detected, the UCD mentioned above.

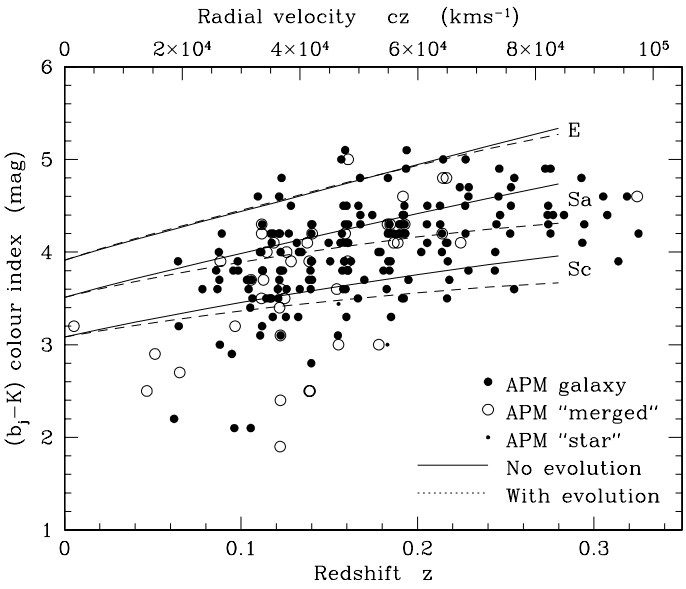

Fig. 2. Optical – IR colour, $b_j - K_s$, versus redshift for matched PSC objects with galaxy spectra. Different optical image morphologies are indicated. The model tracks are from Poggianti (1997).

The PSC sample goes ∼1 magnitude deeper in K than the XSC sample (and 2 magnitudes deeper than the quoted completeness limit of the XSC), though with less well determined selection criteria. There is rather little overlap in magnitude with the XSC sample, as the vast majority of the PSC galaxies have $14.5 \leq K_s \leq 15.5$ (see Fig. 3 below). The numbers as a function of magnitude suggest that the PSC sample is fairly complete to $K_s \simeq 15.5$. Kochanek et al. (2001) show that at these magnitudes the canonical 0.6 slope fits the counts rather well, so going 1 magnitude deeper we should get a factor 4 more detections, compared to the observed 315/91 = 3.5 for the ratio of XSC and PSC non-cluster galaxies. This means that the PSC is a rich source of moderately faint galaxies not included in the XSC due to their lack of spatial extension. XSC galaxies represent only ∼29% of the (non-cluster) galaxies actually measured by 2MASS in this area. Virtually all (99%) of the galaxies revealed by their spectra could also have been found purely in terms of optical image classification (provided one included "merged" images among the potential galaxies). Thus, with the benefit of the results obtained from all-object surveys such as ours we extend the search for PSC galaxies by simply matching to, say, resolved images in APM or SDSS data. Note however, that a substantial fraction of the PSC galaxies will be fainter than the SDSS or even 2dF spectroscopic limit, and the "merged" images would remain problematic.

[3] The outlier with the *very* blue $b_j - K_s$, FCC222, is in the Arp & Madore (1987) catalogue with several classifications in different sources and strange spectral characteristics (Mieske et al. 2002). Its colour may also be rather uncertain, its b_j magnitude in the SuperCOSMOS sky survey (Hambly et al. 2001) is 16.2 compared to our 15.1. Mieske et al. (2002) give $V = 14.9$ and the eye estimate in the FCC is $B = 15.6$. SuperCOSMOS gives a more reasonable $b_j - K_s = 2.8$.

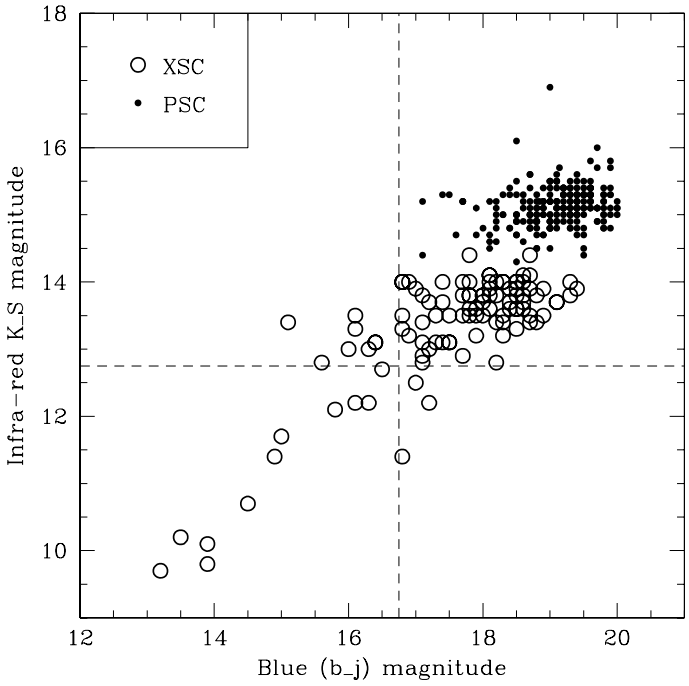

Fig. 3. A b_j (Drinkwater et al. 2001a) vs. K_s plot of our XSC sample, PSC sample and 6dfGRS completeness limits. XSC magnitudes were slightly underestimated in the 2MASS 2nd data release (see C2001) accounting for some of the gap between the XSC and PSC galaxies.

Template matching suggests that in this deeper sample 43% of the galaxies (97/225) are now best fitted by a K star spectrum (slightly fewer than before) and 33% (75/225) by G or F star spectra. This implies a significant shift towards the "intermediate" type spectra for these objects, which are forced towards slightly bluer $b_j - K_s$ since they are fainter in K_s than the XSC objects, but have the same b_j limit. Intermediate types predominate amongst the most distant matched objects; again suggesting the loss of the reddest galaxies. Only 23% (53/225) of the PSC/FCSS objects are fitted by emission line templates (essentially the same as in the XSC sample), compared to almost 50% of FCSS objects as a whole, i.e. 2MASS has a lower content of star forming galaxies than does a blue selected sample. Indeed, 680 of the FCSS galaxies (and 55 AGN) are *not* bright enough in the near IR to enter the 2MASS catalogues. Thus, only ~300 out of 1000 FCSS galaxies are in 2MASS, whereas ~1800 of 2200 stars are present: in the same, fixed optical magnitude range, galaxies are far *less* likely to be included in the 2MASS catalogues than stars, again because of a combination of their surface brightnesses and colours. As we have seen, cluster dwarf galaxies are less likely still[4].

Given that many galaxies are not large enough to appear in the XSC, it is appropriate to consider whether unresolved objects have an impact on the IR galaxy luminosity function. C2001 have already made careful allowance for this, using the expected isophotal radii of galaxies to correct for the numbers lost because of the rather large isophotal diameter limit implied for the XSC (see also Andreon 2002). As previously stated, our PSC and XSC samples have little overlap in K_s band magnitude and no overlap with the brighter, complete sample from the XSC. Thus few galaxies which should have been present at, say, $K_s = 14.5$ have in actuality been overlooked because of their small size. Thus existing LFs from data limited at $K_s \leq 14.5$ should not suffer from significant incompleteness.

The caveat is that there may be galaxies which, because of the isophotal limit, fail to make the cut for either the XSC or the PSC. In particular, low surface brightness galaxies could have very low signal-to-noise ratios in the IR bands. As noted above, our matched sample actually contains rather few dwarfs, which typically are of low surface brightness. As we do not yet have an accurate distribution of optical to IR colours for dwarfs and other low surface brightness galaxies, it is not possible to estimate how many of the optically selected dwarfs should have been included in the 2MASS samples purely on the grounds of their total magnitudes but were omitted because of their surface brightness. The Millennium Galaxy Catalogue (Driver et al. 2005) should give a good indication of the numbers of low surface brightness objects that might be missed (assuming plausible optical/IR colours).

Some implications of this work for other surveys based on the XSC, for example, the 6dfGRS (Jones et al. 2004) are shown in Fig.3. The 6dfGRS XSC galaxies were supplemented by other catalogues including SuperCOSMOS (Hambly et al. 2001) allowing us to plot the completeness limits at $b_j = 16.75$ and $K_s = 12.75$. The extra PSC galaxies are below the faint limit of the 6dfGRS (dashed lines) confirming its completeness to its stated limits.

[4] 60% of missed FCSS galaxies have emission line spectra, 29% match G, F or A star spectra and only 11% K or M type spectra.

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