

# Intergalactic stars in the Fornax cluster

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## ABSTRACT

We have identified 10 candidate intergalactic planetary nebulae in the Fornax galaxy cluster. These objects were found during observations in 1992 and 1993 in three fields chosen well away from any Fornax galaxy at 15, 30 and 45 arcmin from the centre of Fornax. We used the usual method of blinking images taken in a narrow [O III]  $\lambda 5007$ -Å filter with images taken in an adjacent broad filter. The measured fluxes in the narrow, broad and *I* bands are consistent with these unresolved objects being planetary nebulae immersed in an intergalactic population of stars. Such a population is expected to arise as a consequence of tidal encounters between galaxies, and our findings strengthen the case for the existence of such tidal debris. The confirmation of some or all of these 10 candidates as planetary nebulae would imply that intergalactic stars constitute a substantial fraction of all the stars in Fornax, up to an estimated ~40 per cent. Intergalactic planetary nebulae could prove useful in probing the underlying cluster potential, since they would be far more abundant than galaxies. We discuss possible contamination of the sample by emission-line galaxies, but conclude that planetary nebulae comprise the most likely identification for the detected objects.

**Key words:** planetary nebulae: general – galaxies: clusters: individual: Fornax – galaxies: interactions – intergalactic medium.

## 1 INTRODUCTION

Tidal interactions between galaxies in a cluster are expected to be frequent and may induce structural changes in the disturbed galaxies. For example, numerical simulations by Moore et al. (1996) indicate that fast tidal encounters produce ‘harassed’-looking galaxies, reminiscent of the distorted spirals in clusters at a redshift of  $\sim 0.4$  as observed by the *Hubble Space Telescope*. Numerical simulations of the evolution of galaxies in a cluster (e.g. Roos & Norman 1979; see Dressler 1984 for a review) suggest that these tidal encounters cause galaxies to lose a substantial fraction, 30–70 per cent, of their stars to the cluster potential where they are left free to roam as intergalactic tidal debris.

Zwicky (1951) associated excess light he had observed between the galaxies in Coma with such debris from tidal interactions. Subsequent searches for intergalactic light in clusters of galaxies (usually in Coma) and Hickson’s compact groups, using photographic plates, direct photometric observations or CCD imaging, were not all equally conclusive (e.g. de Vaucouleurs & de Vaucouleurs 1970; Vilchez, Pello & Sanahuja 1994, and references therein), with many observers concluding that the amount of intergalactic light could be attributed to low surface brightness galaxies, inaccurate subtraction of foreground stars and haloes of galaxies. Another line of attack to track down the debris is to look for intergalactic supernovae. Of the 13 supernovae detected in

Coma over a period of 15 effective search years, Crane, Tammann & Woltjer (1977) could associate all of them with galaxies, either in Coma or in the background. They concluded that the intergalactic debris in Coma is at least six times less active per unit light in producing supernovae than the Coma galaxies are. Harris (1986), following up ideas of Merritt (1983, 1984), suggested that the central galaxy in a cluster might be surrounded by a population of globular clusters, stripped from their parent galaxies. This proposal was investigated by Muzzio (1987, and references therein) and more recently by West et al. (1995), who suggest that the pronounced globular cluster overabundance of some galaxies in the centres of galaxy clusters is best explained by assuming the existence of a population of intergalactic globular clusters.

In this Letter we report on the identification of 10 candidate intergalactic planetary nebulae (PNe) in the Fornax galaxy cluster. Fornax [ $\alpha = 3^{\text{h}}38^{\text{m}}29^{\text{s}}$ ,  $\delta = -35^{\circ}27'$  (J2000.0), distance  $17 \pm 1$  Mpc: McMillan, Ciardullo & Jacoby (1993)] is a poor, dense cluster of galaxies, relatively rich in early-type galaxies (ratio of early to late types a factor of two higher than in Virgo: Ferguson 1989). It has a high central density of galaxies (500 per Mpc<sup>3</sup>) and a low velocity dispersion (350 km s<sup>-1</sup>: Ferguson 1989). Its central galaxy, NGC 1399, is a cD galaxy with both an extended halo of diffuse light (Schombert 1986; Warren, Theuns & Williger, in preparation) and an abundant and extended globular cluster population (Grillmair et al. 1994, and references therein). All these

properties suggest that Fornax should have a substantial population of intergalactic stars. Since these stars should be similar to the stars in the galaxies, they would also have a sub-population of PNe. The detection of intergalactic PNe as far away as Fornax is feasible technically, since PNe within galaxies in Fornax have already been found. McMillan et al. (1993) used narrow-band imaging to identify 72 candidate PNe in NGC 1399. Arnaboldi et al. (1994) later obtained spectra for 54 of them and they were able to obtain velocities for a subset of 37. We have used the same technique to search for intergalactic stars.

In Section 2 of this Letter we describe our observational strategy to detect the brightest PNe in three fields in the Fornax cluster, and detail the standard reduction and selection procedures. Section 3 summarizes our findings, and Section 4 contains a discussion of our results.

## 2 OBSERVATIONS

### 2.1 Set-up and data reduction

We have imaged three fields in the Fornax cluster in narrow, broad and *I* bands, using the EMMI instrument on the New Technology Telescope at the European Southern Observatory, La Silla, Chile. The fields are located at angular separations of 15, 30 and 45 arcmin from the centre of NGC 1399. The coordinates of the fields are provided in Table 1, and the locations are shown in Fig. 1 (opposite). The dates of the observations were 1992 December 30 and 31, and 1993 November 19, 20 and 21. Conditions were mostly clear, with some thin cirrus at times. Details of the average seeing (image FWHM in the combined frames), and integration times are provided in Table 2. The narrow-band and broad-band filters were used in the blue arm (BIMG), where the scale is 0.37 arcsec per pixel. The *I*-band observations were made with the red arm (RILD), with the old *f*/2.5 camera, for which the scale was 0.44 arcsec per pixel in 1992, with the Thomson chip, and 0.35 arcsec per pixel in 1993, with the Ford chip.

The narrow-band filter has FWHM 29 Å and is centred at  $\lambda_c = 5028$  Å, very close to the wavelength of [O III]  $\lambda 5007$  Å redshifted to the velocity (1422 km s<sup>-1</sup>) of NGC 1399. In EMMI the blue filters lie in a diverging *f*/11 beam, so the broadening and blueshift of the transmission curve, relative to the laboratory curve (measured in a parallel beam), may be neglected. The broad-band filter has FWHM 286 Å and is centred at  $\lambda_c = 4714$  Å. Integration times, filter transmission, telescope size and seeing are comparable to those for the runs of McMillan et al. (1993), so we expect our observations to reach slightly fainter than theirs since they had to find PNe on top of the bright parent galaxy.

After the usual dark and bias subtraction and flat-fielding, we combined the individual images for a given field. The combining procedure weights the frames by the inverse of the variance in the sky, and also compares the respective pixel values for the individual

Table 2. Observing log.

field	date	filter	no. of frames	average seeing arc sec.	total int. time s
1	Nov 93	narrow	3	1.0	9900
1	Nov 93	broad	4	1.0	7200
1	Nov 93	I	2	1.1	720
2	Dec 92	narrow	4	1.2	13200
2	Dec 92	broad	5	1.3	6300
2	Dec 92	I	4	0.9	960
3	Nov 93	narrow	4	1.0	13200
3	Dec 92	broad	2	1.1	2400
3	Nov 93	broad	5	1.1	6000
3	Dec 92	I	4	0.9	960

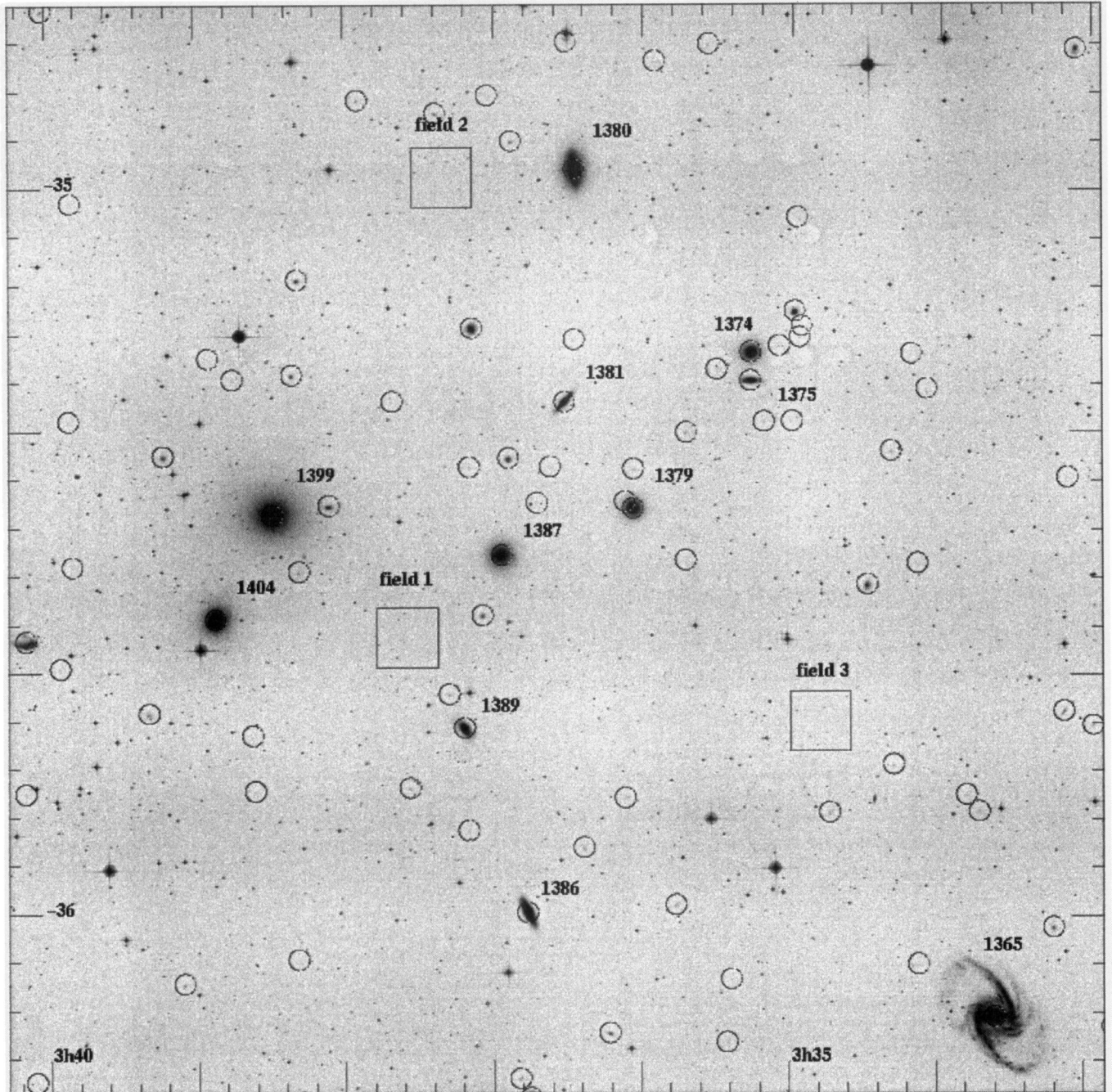
frames to detect and eliminate cosmic rays. The final frames in each field cover an area of  $5.9 \times 5.9$  arcmin<sup>2</sup>. We flux calibrated the broad-band and narrow-band frames on to the AB system using observations of the standard stars Hiltner 600 and LTT1788 (Hamuy et al. 1992). For the *I*-band frames we used standards from Landolt (1992), on the Kron-Cousins system. Conditions were not always photometric. However, because we have a number of frames in each field, as well as multiple observations of standard stars, we were able to keep track of the extinction due to clouds, which was only ever at the level of 0.1 mag or less. By identifying those observations taken when the sky was clear we were able to calibrate the fields, and we estimate that the photometric zero-points are accurate to 0.05 mag. This is borne out by a comparison between the fields of the median narrow-broad colour  $m_n - m_b$  of all the objects in the field. The scatter between the three fields of the median colour is  $\sigma = 0.04$  mag.

### 2.2 Analysis

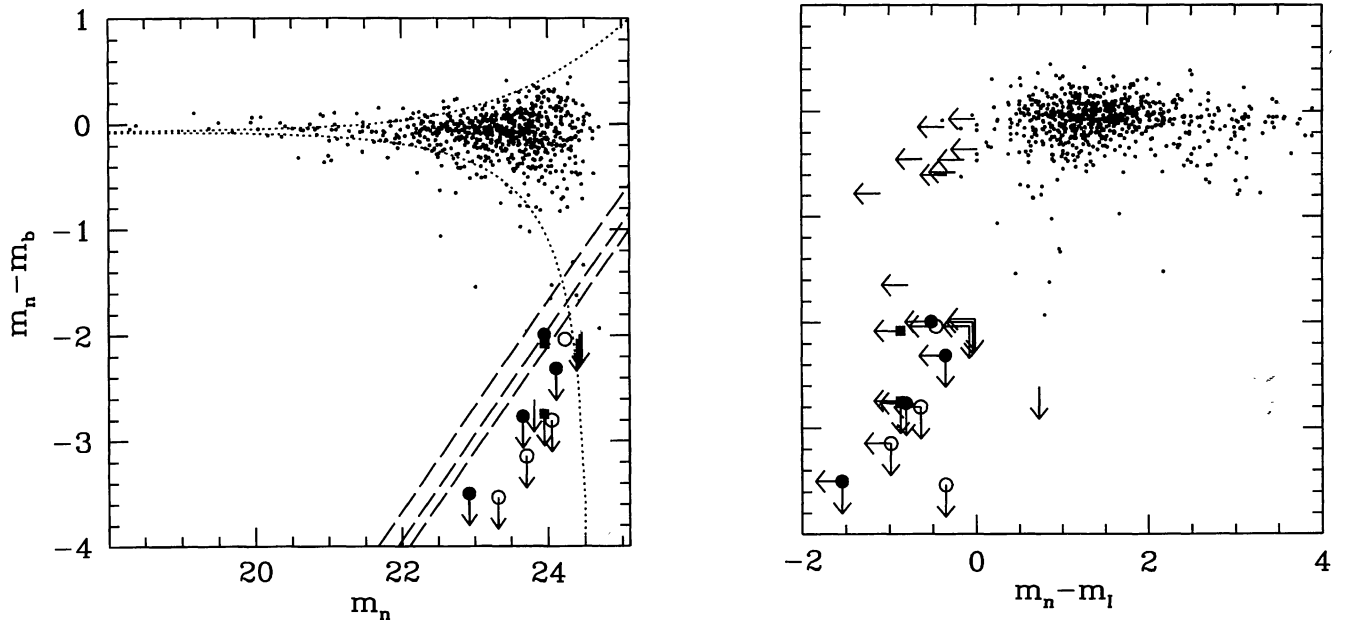
From a knowledge of the luminosity function of PNe, the exposure times, the distance to Fornax and the very large expected equivalent widths (EWs) of the [O III]  $\lambda 5007$ -Å line, most likely any PNe visible in our narrow-band frames will be absent from the broad-band and *I*-band frames. Based on this, we have used the following procedure to identify candidate PNe. Using the photometry package DAOPHOT (Stetson 1987), we produced a source list for each narrow-band frame, restricted to objects detected at greater than 4 $\sigma$  significance, as measured by aperture photometry using an aperture of diameter twice the stellar FWHM. Next, resolved sources were eliminated, using the DAOPHOT procedure PEAK, which compares the profile of each object against the point-spread function obtained from bright stars. Using a six-parameter transformation the coordinates of these sources in the other bands were computed, and the magnitudes were measured at these positions, i.e. without recentering, again using an aperture of twice the stellar FWHM for the particular frame. This procedure is designed for sources that are very faint in these bands, for which the centring algorithm would not work well. Finally, we assigned fluxes corresponding to 1 $\sigma$  above sky to objects with measured fluxes below this level. This produced magnitudes in the narrow, broad and *I* bands (denoted here by  $m_n$ ,  $m_b$ ,  $m_I$  respectively) for our basis set of objects. The 1 $\sigma$  detection levels, averaged for the three fields, are  $m_n = 26.0$ ,  $m_b = 26.7$ ,  $m_I = 24.7$ .

Table 1. Coordinates of observed fields.

field	RA	Dec.
	J2000.0 equinox	
1	3 37 35	-35 37 15
2	3 37 17	-34 59 10
3	3 34 48	-35 44 05



**Figure 1.** A region of size 90 arcmin in Fornax drawn from the Digitized Sky Survey (J2000.0 equinox). The major Fornax galaxies are indicated by their NGC numbers; NGC 1399 is usually taken to be the centre of Fornax. Circles denote galaxies that are likely to be Fornax members, according to Ferguson (1989). The three fields are indicated by squares of side 5.9 arcmin. For the adopted distance  $d = 17$  Mpc, the field of view corresponds to 445 kpc on a side.



**Figure 2.** Colour–magnitude (left panel) and colour–colour (right panel) diagrams for objects in fields 1–3. Dots denote objects detected in the corresponding bands; arrows denote  $1\sigma$  upper limits for non-detections. Objects satisfying all selection criteria (see text) are plotted as filled circles (field 1), filled squares (field 2) and open circles (field 3). Left panel: objects within  $3\sigma$  of the median colour fall inside the dotted lines. The dashed lines show the  $2\sigma$  detection limits for the broad band, for each field. Candidate intergalactic PNe are objects that fall below both these selection limits, and are bluer than  $m_n - m_I = 0.0$ .

### 3 RESULTS

The results of the photometry are illustrated in Fig. 2, which shows  $m_n - m_b$  versus  $m_n$  colour–magnitude and  $m_n - m_b$  versus  $m_n - m_I$  colour–colour diagrams. These diagrams can be used to select candidate intergalactic PNe. Any PNe in our frames will have unusual colours relative to the locus of common objects visible in the plots, which comprise Galactic stars and compact galaxies. Candidates were selected using the following criteria:

- (1) the  $m_n - m_b$  colour differs, in the negative direction, by more than  $3\sigma$  from the median  $m_n - m_b$  for all objects in the frame – such objects fall below the lower dotted line in Fig. 2, left panel;
- (2) the objects are not detected at  $\geq 2\sigma$  in the broad-band frame – such objects fall below the dashed lines in Fig. 2, left panel;
- (3) objects have  $m_n - m_I < 0.0$ .

Criterion (1) requires that the candidates have significant excess flux in the narrow-band frame relative to the flux in the broad-band frame. Criterion (2) states that the line EWs are consistent with being large: at the  $2\sigma$  level they are consistent with being infinite. Criterion (3) is an attempt to remove compact emission-line galaxies from the sample. In particular, galaxies in these fields at  $z = 0.35$ , for which the line  $[\text{O II}] \lambda 3727 \text{ \AA}$  falls in the narrow-band filter, but which have a substantial  $4000 \text{ -\AA}$  break, will be eliminated by this means.

Application of the above selection criteria leads to the identification of four, two and four candidates in fields 1, 2 and 3 respectively. We have checked the images of each candidate in every CCD frame used to make the combined frames, to ensure that the unusual colours are not due to flaws in individual frames, or e.g. cosmic rays, or satellite trails. The candidates have narrow-band magnitudes in the range  $22.9 < m_n < 24.2$ . The estimated line fluxes<sup>1</sup> are in the range  $9.5 \times 10^{-17} > F_{5007} > 2.9 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ , and  $26.3 < m_{5007} < 27.6$ , where as usual  $m_{5007} = -13.74 - 2.5 \log F_{5007}$ . None of the candidates is detected at greater than  $2\sigma$  significance in the broad band. In the  $I$  band the brightest

candidate in field 3 is possibly detected at  $2.5\sigma$ , while the remaining nine candidates are fainter than the  $1\sigma$  level.

### 4 DISCUSSION

To summarize the previous sections, we have discovered 10 objects in our fields whose angular sizes and magnitudes in the three bands are consistent with their being intergalactic PNe in the Fornax cluster. We now consider in more detail whether any of the candidates could be distant galaxies, rather than PNe, because either  $[\text{O II}] \lambda 3727 \text{ \AA}$  ( $z = 0.35$ ) or  $\text{Ly}\alpha \lambda 1216 \text{ \AA}$  ( $z = 3.14$ ) falls within the narrow-band filter. The question is not straightforward to answer as there are few surveys that reach the faint line-flux limits of our narrow-band images, and the continuum fluxes of our candidates,  $m_b > 26$ ,  $m_I > 24$ , are beyond the limits of the faintest magnitude-limited spectroscopic surveys. Nevertheless, the lower redshift appears unlikely. The mean rest-frame EW of the candidates if at  $z = 0.35$  is  $> 250 \text{ \AA}$ , and such large EWs have not been seen for  $[\text{O II}]$  in deep galaxy surveys (Colless et al. 1990; Cowie, Hu & Songaila 1995). Furthermore, galaxies at this redshift would likely be resolved in our frames.

We can check whether the higher redshift  $z = 3.14$  is a possibility by making a direct comparison against the results of the emission-line searches for high-redshift galaxies by Lowenthal et al. (1995) and Thompson, Djorgovski & Trauger (1995). On the basis of their quoted detection limits, if our candidates are galaxies at  $z = 3.14$ , we estimate that in each of these surveys three galaxies at  $z > 2$  would have been found above the  $3\sigma$  detection limits, whereas none was discovered. This is fairly clear evidence against our candidates being galaxies at  $z = 3.14$ .

On the basis of the foregoing we consider it likely that our

<sup>1</sup>The line fluxes were calculated from  $F_{5007} = f_\lambda \int T_\lambda dN T_L$  where  $f_\lambda$  is the flux per unit wavelength of a continuum source with the same  $m_n$ ,  $T_\lambda$  is the transmission of the filter as a function of wavelength, and  $T_L$  is the average transmission over the central few angstroms.

candidates are intergalactic PNe. We have also compared the distribution in luminosity of our candidates against the luminosity function of Ciardullo et al. (1989). A Kolmogorov–Smirnov (KS) test indicates a satisfactory fit, which increases our confidence in our identification. Just before completing this Letter we received a preprint by Arnaboldi et al. (1996) who, while searching for PNe in the outer halo of the Virgo elliptical NGC 4406, serendipitously found three PNe with radial velocities widely different from that of the target galaxy. They concluded that these PNe may be intergalactic stars in the Virgo cluster. With the wide-field CCD cameras becoming available, it appears that it may now be possible to detect intergalactic PNe in large numbers.

Proceeding on the assumption that our 10 emission-line candidates are intergalactic PNe, we next try to estimate the contribution of intergalactic stars to the total light in the Fornax cluster. Our observations reach about one magnitude below  $M^*$  in the PN luminosity function, and we adopt the value for the luminosity-specific planetary nebula density for M31,  $\alpha_{1.0(B)} = 9.4 \times 10^{-9}/(L_B)_\odot$  (Ciardullo et al. 1989). [We note, however, that the value of  $\alpha_{1.0(B)}$  is probably different for different stellar populations (Hui et al. 1993), and therefore the chosen value may not be appropriate for intergalactic debris.] We surveyed  $104 \text{ arcmin}^2$ , so this provides an estimate for the surface brightness in tidal debris of  $1.0 \times 10^7 (L_B)_\odot$  per  $\text{arcmin}^2$ . The total luminosity contributed by galaxies contained in the central  $200 \times 200 \text{ arcmin}^2$  region of Fornax is  $\sim 6.6 \times 10^{11} (L_B)_\odot$  (Caldwell 1987), corresponding to a surface brightness of  $\sim 1.65 \times 10^7 (L_B)_\odot$  per  $\text{arcmin}^2$ . Comparing these two values we estimate that the contribution of intergalactic stars to the total light in the Fornax cluster could be as much as  $\sim 40$  per cent.

To summarize, with narrow-band imaging we have searched for intergalactic PNe in the Fornax cluster, and discovered 10 good candidates, which require spectroscopic confirmation. Future surveys could detect hundreds of such objects. Intergalactic PNe may, therefore, prove invaluable in the study of cluster dynamics.

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