Evidence for Sub-Populations in Globular Clusters: Their Properties and Relationship with Cluster Properties

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An increasing number of both photometric and spectroscopic observations over the last decade have shown the existence of distinct sub-populations in some Galactic globular clusters. This evidence severely challenges the paradigm of globular clusters as the prototypes of single, simple stellar populations. In this review, we briefly summarise the main empirical findings collected so far and discuss the properties of these sub-populations and their possible relationship with global cluster properties.

The scientific framework

Globular clusters (GCs) still occupy a pivotal role in current astrophysical research. As the oldest population II objects for which accurate ages can be inferred, they place an important constraint on the age of the Universe and, in turn, on cosmology. In addition, the analysis of the chronology of the Galactic GC system can provide fundamental information on the formation process of the Galaxy. For a long time GCs have represented an ideal laboratory for testing and calibrating stellar evolutionary models. In addition, since they are regarded as consisting of coeval and chemically homogeneous stars, they have been considered as the prototype of Simple Stellar Populations (SSP). In consequence, GCs have been employed as an ideal template for checking the accuracy and reliability of the population synthesis tools that are used to retrieve the properties of unresolved stellar populations.

Up until a few years ago the interpretation of the available colour-magnitude diagrams (CMDs) of GCs in the framework of theoretical stellar evolution fully supported the view of GCs as SSP (see, for instance, King et al., 1998). However there is a growing body of empirical findings that severely challenges this traditional view. In fact, accurate spectroscopic surveys of sizable samples of GC stars made after 1980 have revealed that GCs show a peculiar pattern in their chemical abundances: while they are generally – with very few exceptions – very homogeneous in the abundances of Fe-peak elements, GC stars show very clear anticorrelations between the abundances of C and N, Na and O, Mg and Al (for a full review of this issue we refer to Gratton et al., 2004) that are not predicted by canonical stellar models. It is worth noting that this pattern is characteristic of GC stars, since, in field stars, the observed trend for C and N abundances is consistent with the theoretical evolutionary predictions. This occurrence strongly supports the idea that the GC environment must play a role in the appearance of these chemical peculiarities. More importantly, accurate spectroscopic measurements of both dwarf and giant stars in GCs show that the observed chemical pattern is primordial, as it is also present in unevolved stars (Gratton et al., 2001), and, does not only involve the envelopes of the stars, i.e., it is not a simple pollution effect (Cohen et al., 2002).

Although there is no doubt that the observed anticorrelations are due to the fact that a fraction of the GC stars have formed from matter that has been polluted with the yields of high temperature H-burning (see Salaris et al., 2002, for a review), there is still some debate about what is responsible for this pollution: asymptotic giant branch (AGB) stars (Ventura et al., 2001) or fast-rotating massive stars (Decressin et al., 2007).

Many GCs also show a very peculiar Horizontal Branch (HB), with the presence of an extended blue tail (Recio-Blanco et al., 2006) and/or a clumpy distribution of stars characterised by the presence of one or more gaps (Ferraro et al., 1998; Piotto et al., 1999). These peculiarities in the horizontal branch morphology are commonly known as 'the second parameter problem', and we have not yet achieved a full understanding of their origin. In recent times the existence of a possible link between the HB morphology and the peculiar chemical patterns has been suggested (D'Antona & Caloi, 2004): matter processed via high temperature H-burning should also be enriched in He content, and it is known that a change in the initial abundance of He produces remarkable changes in stellar properties at the HB stage.

Thus, several independent observational findings seem to suggest that, at least in some GCs, there is a sizable fraction of stars that have formed from material that must have undergone nuclear processing by a previous generation of stars. In this context, it is clear that the fundamental question is whether we can find direct, straightforward evidence for the existence of multi-populations in some GCs?

Over the last few years, the availability of high quality photometry on deep HST images and multi-object spectroscopy has provided this evidence. So far, the presence of different sub-populations has only been proved in a few clusters, but the search is still ongoing and there are other GCs that are thought to host multiple populations. In the following, we briefly summarise the evidence collected so far for multi-populations, and discuss the possible link with the global properties of the parent GC.

The chief suspects: direct, observational evidence for multi-populations in GCs

The GCs in which indisputable, direct evidence of the presence of multiple populations has been found, are: ω Centauri, NGC 2808, NGC 1851, NGC 6121, NGC 6388 and M54. The last is considered to be the compact nucleus of the dwarf galaxy Sagittarius, currently being accreted by the Milky Way. However it is still under debate which of the sequences observed in the CMD of M54 represents the true cluster population and which are due to stars belonging to Sagittarius dwarf (Siegel et al., 2007). For this reason, we will not discuss this GC further.

ω Centauri

The observational evidence collected over the last 40 years indicates that this GC is the most peculiar object among Galactic GCs in terms of structure, kinematics and stellar content. It is the only known GC showing a clear metallicity spread and it is the most massive one. In the last decade, both extensive spectroscopic and photometric surveys on large samples of giant stars have shown that the distribution of stars in metallicity, as well as in colour, along the red giant branch (RGB) is clearly multi modal (Pancino et al., 2000; Sollima et al., 2005; and references therein), as shown in Figure 1. Specifically, Pancino et al. (2000) have shown the presence of a peculiar RGB (the so-called RGB-a), associated with a metal-rich population ([Fe/H] ~ –0.6) that corresponds to about 5 % of the whole cluster stellar population. Sollima et al. (2005) have identified three metal-intermediate components (–1.3 < [Fe/H] < –1.0) in addition to the dominant population ([Fe/H] ~ –1.6).

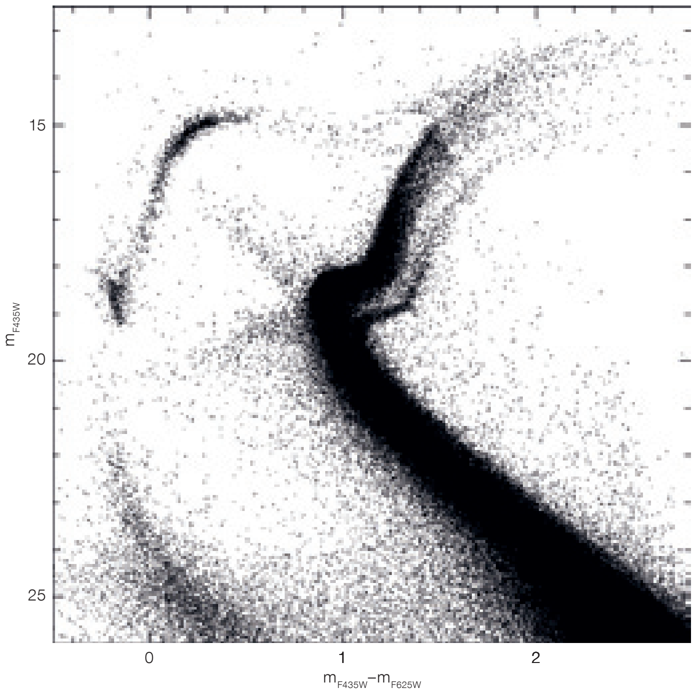

Figure 1. The colour-magnitude diagram of ω Centauri (from Villanova et al., 2007).

Accurate observational analysis has shown that some significant differences do exist among the metal-rich, the metal-intermediate and the metal-poor components, as far as both the spatial distribution (Pancino et al., 2003) and the kinematical properties (Ferraro et al., 2002) are concerned, although Pancino et al. (2007) found no evidence of a difference in the rotational pattern among the various sub-populations. Sollima et al. (2005) obtained the same result for the radial velocity distribution, but they also discovered that the metal-rich component shows a larger velocity dispersion, thus appearing kinematically warmer than the metal-intermediate sub-population.

The most surprising recent result was the discovery by Bedin et al. (2004; but see also Anderson, 1997) that, over a range of at least two magnitudes, the Main Sequence (MS) splits into a red sequence and a blue sequence. Follow-up spectroscopic analysis from GIRAFFE on the VLT (Piotto et al., 2005) leads to even more intriguing results: at odds with any expectations from canonical stellar models, the bluer sequence is more metal-rich than the red one. Until now, the only plausible explanation of the photometric and spectroscopic properties of the double MS is that the blue MS is populated by stars with a high helium content of Y ~ 0.38 (Norris, 2004; Piotto et al., 2005; Lee et al., 2005).

One of the main problems with this scenario is identifying the mechanism responsible for this huge production of helium. So far, various helium producers have been proposed, such as AGB stars (e.g., Ventura & D'Antona, 2008, and references therein), massive rotating stars (Decressin et al., 2007) or even population III stars (Choi & Yi, 2007). However, the properties of He-enriched populations appear to leave only the AGB scenario as viable, even if it still faces some quantitative difficulties (Renzini, 2008).

Even just a few years ago, only rough estimates of the relative ages of the sub-populations hosted by ω Centauri had been obtained, using broad- and narrowband photometry (see for instance, Hughes et al., 2004, and references therein). Recently, however, more detailed analyses have been performed by taking advantage of the most up-to-date photometric and spectroscopic observational facilities (Sollima et al., 2005; Stanford et al., 2006; Villanova et al., 2007; Calamida et al., 2008). The various investigations have obtained quite different, if not contradictory, results concerning the age-metallicity relation: in some cases no age difference is obtained for the different sub-populations; in other cases the metal-rich component is found to be younger by about 2–4 Gyrs with respect to the more metal-poor component; finally independent studies have found the existence of a significant age spread among the metal-poor and metal-intermediate components, with the metal-rich one being the older sub-population. It is worth noting that these different results could partially be accounted for by the fact that different regions of the clusters are sampled in the various analyses, and that the presence of a population gradient in ω Centauri is well-established. In addition, part of the difference in the age results can be attributed to the different theoretical frameworks, distance and reddening estimates used in the various analyses.

It is evident that a detailed study of the chemical abundances and a more complete photometric sampling of the different sub-populations identified in ω Centauri is badly needed in order to understand the complex star formation history of this cluster better.

NGC 2808

This GC is one of the most peculiar Galactic clusters in many respects: for a long time the morphology of its HB has been known to be highly bimodal, with the presence of one or more gaps in the stellar distribution (Bedin et al., 2000); it presents – together with M13 – the strongest O-Na anticorrelation among the Galactic GC population. In addition, Carretta et al. (2006) have shown that it is possible to identify three different subgroups of RGB stars on the basis of their O abundances: O-normal, O-poor and super O-poor components. On the basis of the possible existence of a correlation between O and He content, one can hypothesise the existence in this GC of three distinct sub-populations of stars, each characterised by a different He content. A direct comparison between the star counts for the different stellar groups along the HB, and the sub-groups identified by Carretta et al. (2006), shows the presence of a rather straightforward correspondence between the stars along the RGB and their progeny on the HB: the red HB stars would be those that formed with O-rich/Na-poor/He-poor composition, while the other two groups of RGB stars would contribute to forming the stars that populate the hottest portion of the HB.

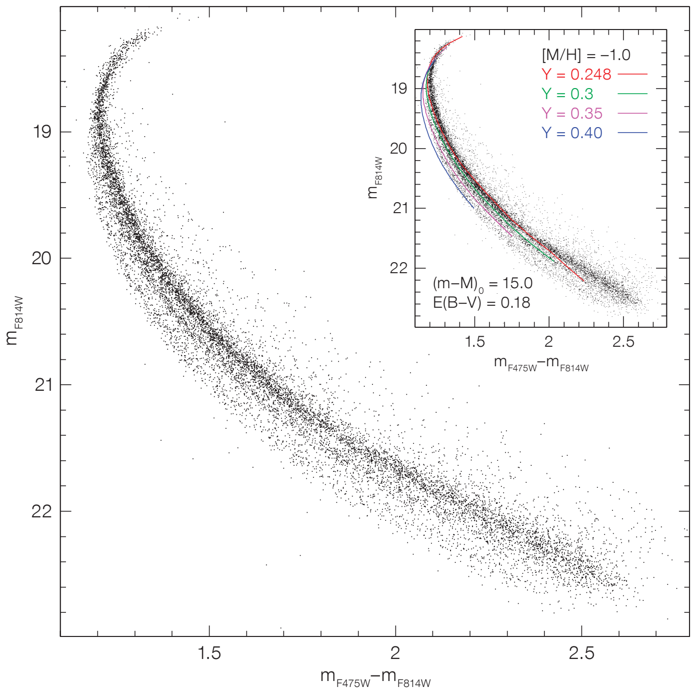

Figure 2. The triple main sequence of NGC 2808. The inset shows the comparison with suitable sets of isochrones computed for different assumptions on the initial helium content (from Piotto et al., 2007).

However, the most amazing result was the discovery by Piotto et al. (2007) that the MS of NGC 2808 is split into three loci. The unique scenario found for interpreting this occurrence is to assume that the three MSs correspond to stars with three different He contents (see Figure 2). The self-consistency of this interpretation with the empirical evidence collected for both RGB and HB stars is really intriguing.

This GC, which clearly hosts multiple stellar populations, is the most massive one after ω Centauri.

NGC 1851

Accurate HST/ACS photometric data have provided indisputable evidence that this cluster hosts at least two distinct sub-populations (Milone et al., 2008): there is a clear splitting in the sub-giant branch (SGB) region (see Figure 3) in its CMD. If the brightness difference between the two SGBs were due only to an age difference, the two star formation episodes should have occurred with a time delay of about 1 Gyr. However, Cassisi et al. (2008) have shown that the presence of two stellar populations in this GC, one with a normal α-enhanced heavy element distribution, and one characterised by a strong CNONa anticorrelation pattern, could properly account for the observed SGB splitting, without invoking any significant age difference. Interestingly enough, this working scenario seems to be supported by spectroscopic measurements (Hesser et al., 1982) indicating the presence of two groups of stars (CN-strong and CN-weak) and by the recent works by

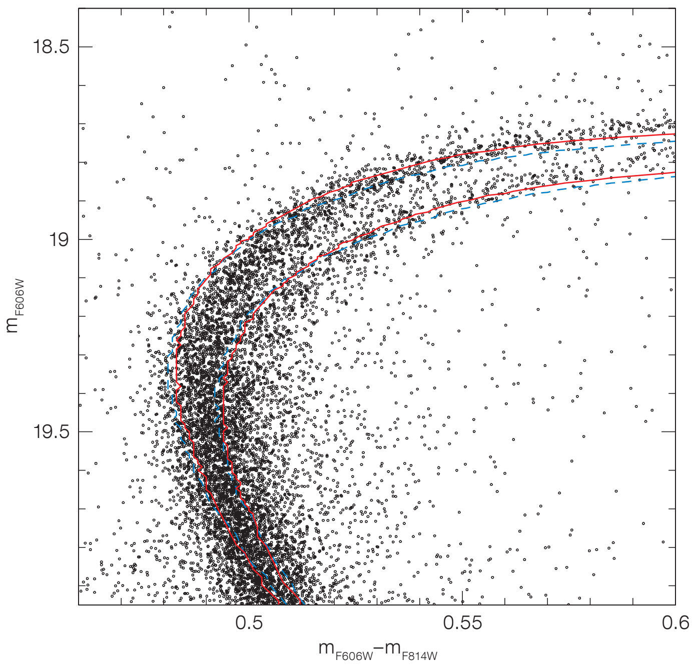

Figure 3. The colour-magnitude diagram of NGC 1851 zoomed around the sub-giant branch. The solid lines represent the isochrones for a stellar population with extreme CNONa anticorrelations and ages of 9 and 10 Gyr. The dashed lines correspond to isochrones for a population with a normal α-enhanced chemical composition and ages of 10 and 11 Gyr.

Yong & Grundahl (2008) and Calamida et al. (2007).

NGC 1851 is considered to be the prototype of bimodal HB GCs. It is intriguing to note that the star counts along the two different SGBs are in remarkably good agreement with those of stars belonging to the two main groups of HB stars. Therefore, one is tempted to look for a link between the different SGB sub-populations among the two groups of RGB stars with distinct CN abundances and the HB stellar sub-populations. In any case, it is evident from both the observed MS width (Milone et al., 2008) and from HB synthetic models (Salaris et al., 2008) that the He enhancement, if any, between the two sub-populations has to be very small (less than 0.03).

Direct spectroscopic measurements of the SGB and HB stars, as well as studies of the mass-loss efficiency among the RGB stars in NGC 1851 (see Salaris et al., 2008, for a discussion on this issue), are mandatory.

NGC 6388

This GC and its twin cluster NGC 6441 are two extremely peculiar clusters. Despite their high metallicity – larger than that of 47 Tuc – they show a bimodal HB, extending towards very hot effective temperatures, a tilt in brightness (Rich et al., 1997; Busso et al., 2007), and a Na-O anticorrelation is present in NGC 6388 (and to a smaller extent also in NGC 6441).

Although both clusters are affected by severe differential reddening, Piotto (2008) has been able to highlight the presence of two distinct SGB loci. No clues about a possible MS splitting have been collected owing to the limitations imposed by the reddening. On account of the close similarities between the two twin clusters, it is plausible that the same outcome could also apply to NGC 6441.

It is worth noting that the peculiar HB morphology of NGC 6388 (and NGC 6441) has been interpreted (Caloi & D'Antona, 2007; Busso et al., 2007) as due to the presence of multiple HB sub-populations characterised by distinct initial He contents, with some spread. How this scenario might be associated with the recent discovery of two SGB sub-populations is an issue that has not yet been addressed.

NGC 6121

Accurate spectroscopic data collected with FLAMES and UVES at the VLT have recently provided the evidence (Marino et al., 2008) that this cluster shows an extended Na-O anticorrelation, and that two distinct groups of stars with significantly different Na and O content are present. In addition, a tight correlation between the NaO and the CN abundances seems to exist. The coupling of the spectroscopic data with accurate photometric evidence has also shown that the two sub-populations with different Na abundances occupy distinct positions (have different colours) along the RGB when the *U*-band (likely influenced by *NH*- and *CN*-bands) is included (see Figure 4). However, due to the dependence of the result on the adopted photometric band, we caution that this empirical finding may not be a genuine proof of the presence in this cluster of distinct sub-populations. We note that the mass of this cluster is an order of magnitude smaller than that of any other GC hosting multi-populations.

A link with cluster properties?

It has already been noted that the five GCs that so far show evidence of the presence of multi-populations, are among the ten most massive clusters in the Galaxy. One may expect that the most massive clusters are more successful in retaining the nuclear-processed ejecta of a first generation of stars, from which a second (or further) stellar generation subsequently formed. However, one has also to note that NGC 1851 is not such a massive cluster, and the situation becomes even more puzzling when considering also the case of NGC 6121, which is a GC with a small mass. The only way to reconcile this discrepancy relies on the plausible assumption that the actual mass of many GCs is just a – sometimes minor – fraction of the initial total mass, as a consequence of tidal shocks with the Galactic disc.

It is also worth noting that almost all clusters hosting multi-populations are also characterised by a high central velocity dispersion. So one could be tempted

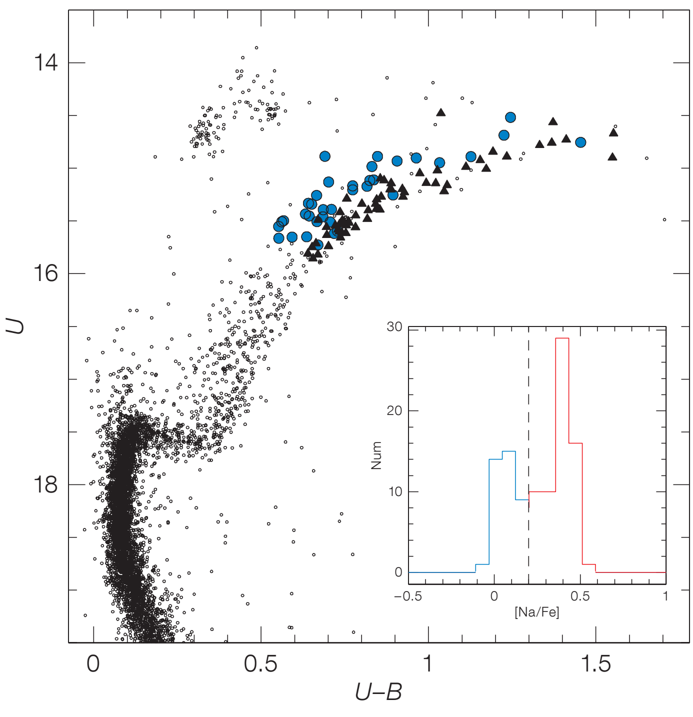

Figure 4. The colour-magnitude diagram of NGC 6121 and the distribution of Na abundance from Marino et al. (2008). The different colours identify the stars belonging to the two different Na groups.

to look for a link between the presence of multi-populations, a high total (initial?) mass and high central velocity dispersion. An interesting working hypothesis would be to associate multi-populations with the presence of an intermediate mass black hole (IMBH).

An observable fingerprint of the presence of an IMBH would be a small slope in the radial density distribution in the core region that would affect the surface brightness profile (Baumgardt et al., 2005; Trenti et al., 2007). Some empirical (Noyola et al., 2008) and theoretical (Miocchi, 2007) indications have been collected that seem to support this possibility.

The expected effects of the presence of an IMBH in the core region of a stellar cluster are: (1) the BH would act as a 'heat source' in the central regions; (2) it would strongly enhance the mass loss of RGB stars passing close by; (3) it could trigger multiple star formation bursts. It is evident that these processes – if really occurring – would allow many of the features observed in the GCs hosting multi-populations to be explained.

The observational framework is becoming more and more complex, but the new empirical findings are of pivotal importance to shed light on the formation and early evolution of GCs. Therefore, we are now on the right path to piecing the jigsaw puzzle together.

References

Anderson, J. 1997, PhD thesis, University of California, Berkeley
Baumgardt, H., Makino, J. & Hut, P. 2005, ApJ, 620, 238
Bedin, L. R. et al. 2000, A&A, 363, 159
Bedin, L. R. et al. 2004, ApJ, 605, L125
Busso, G. et al. 2007, A&A, 474, 105
Calamida, A. et al. 2007, ApJ, 670, 400
Calamida, A. et al. 2008, in preparation
Caloi, V. & D'Antona, F. 2007, A&A, 463, 949
Carretta, E. et al. 2006, A&A, 450, 523
Cassisi, S. et al. 2008, ApJ, 672, L115
Choi, E. & Yi, S. K. 2007, MNRAS, 375, L1
Cohen, J. G., Briley, M. M. & Stetson, P. B. 2002, AJ, 123, 2525
D'Antona, F. & Caloi, V. 2004, ApJ, 611, 871
Decressin, T. et al. 2007, A&A, 464, 1029
Ferraro, F. R. et al. 1998, ApJ, 500, 311
Ferraro, F. R., Bellazzini, M. & Pancino, E. 2002, ApJ, 573, L95
Gratton, R. G. et al. 2001, A&A, 369, 87
Gratton, R., Sneden, C. & Carretta, E. 2004, ARAA, 42, 385
Hesser, J. E. et al. 1982, AJ, 87, 1470
Hughes, J. et al. 2004, AJ, 127, 980
King, I. R. et al. 1998, ApJ, 492, L37
Lee, Y.-W. et al. 2005, ApJ, 621, L57
Marino, A. F. et al. 2008, A&A, in press (astro-ph/0808.1414)
Milone, A. P. et al. 2008, ApJ, 673, 241
Miocchi, P. 2007, MNRAS, 381, 103
Norris, J. E. 2004, ApJ, 612, L25
Noyola, E., Gebhardt, K. & Bergmann, M. 2008, ApJ, 676, 1008
Pancino, E. et al. 2000, ApJ, 534, L83
Pancino, E. et al. 2003, MNRAS, 345, 683
Pancino, E. et al. 2007, ApJ, 661, L155
Piotto, G. et al. 1999, AJ, 118, 1727
Piotto, G. et al. 2005, ApJ, 621, 777
Piotto, G. et al. 2007, ApJ, 661, L53
Piotto, G. 2008, Mem. Soc. Astr. It., 79, 334
Recio-Blanco, A. et al. 2006, A&A, 452, 875
Renzini, A. 2008, MNRAS, in press (astro-ph/0808.4095)
Rich, R. M. et al. 1997, ApJ, 484, L25
Salaris, M., Cassisi, S. & Pietrinferni, A. 2008, ApJ, 678, L25
Salaris, M., Cassisi, S. & Weiss, A. 2002, PASP, 114, 375
Siegel, M. H. et al. 2007, ApJ, 667, L57
Sollima, A. et al. 2005, ApJ, 634, 332
Stanford, L. M. et al. 2006, ApJ, 647, 1075
Trenti, M. et al. 2007, MNRAS, 374, 857
Ventura, P. & D'Antona, F. 2008, MNRAS, 385, 2034
Ventura, P. et al. 2001, ApJ, 550, L65
Villanova, S. et al. 2007, ApJ, 663, 296
Yong, D. & Grundahl, F. 2008, ApJ, 672, L29