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THE LOWER MAIN SEQUENCE AND MASS FUNCTION OF THE GLOBULAR CLUSTER MESSIER 4[1]

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ABSTRACT

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[1] Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA under NASA contract NAS 5-26555. These observations are associated with proposal GO-8679.

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The deepest optical image ever in a globular star cluster, a Hubble Space Telescope (HST) 123 orbit exposure (GO 8679, cycle 9) in a single field of Messier 4, was obtained in 2 filters (F606W – V, F814W – I) over a 10 week period in early 2001. A somewhat shallower image obtained in 1995 (GO 5461, cycle 4) allowed us to select out cluster and field objects via their proper motion displacement (PMD) resulting in remarkably clean color-magnitude diagrams (CMDs) that reach to V = 30, I = 28. The cluster main sequence (MS) luminosity function (LF) contains very few stars fainter than $M_V = 15.0$, $M_I = 11.8$ which, in both filters, is more than 2 magnitudes brighter than our limit. This is about the faintest luminosity seen among field Population II subdwarfs of the same metallicity. However, there remains a sprinkling of potential cluster stars to lower luminosity all the way down to our limiting magnitudes. These latter objects are significantly redder than any known metal–poor field subdwarf. Comparison with the current generation of theoretical stellar models implies that the masses of the lowest luminosity cluster stars observed are near $0.09 M_\odot$. We derive the mass function (MF) of the cluster in our field and find that it is very slowly rising towards the lowest masses with no convincing evidence of a turnover even below $0.1 M_\odot$. The formal slope between 0.65 and $0.09 M_\odot$ is $\alpha = 0.75$ (Salpeter = 2.35) with a 99% confidence interval 0.55 – 1.05. A consistency check between these slopes and the number of observed cluster white dwarfs (WDs) yields a range of possible conclusions, one of which is that we have indeed seen the termination of the WD cooling sequence in M4.

Subject headings: globular clusters: individual (Messier 4) – stars: astrometry, low-mass, mass function, white dwarfs

1. Introduction

Analysis of the Hubble Deep Field (HDF) (Williams *et al.* 1995), which is to date the deepest optical image ever taken, has produced a remarkable series of important results both in Galactic and extragalactic astronomy (see Ferguson *et al.* 2000 for a summary). With the original HDF as a model, we proposed to carry out an HDF–like project in the nearest globular cluster, M4. We were successful in obtaining a roughly similar amount of telescope time (123 orbits) for the 2 filters F606W (V – 127,400 sec) and F814W (I – 192,400 sec) as had been granted for the HDF. Our plan was to reach V $\sim$ 30, I $\sim$ 28 with s/n about 3 in each filter in a single M4 field located 6 core radii ($\sim 5'$) from the cluster center – the same field which we observed in 1995 (GO 5461).

The main science driver was to search for the oldest and coolest white dwarfs (WDs) in M4. The discussion of the WD population in M4 is contained in the following *Letter* (Hansen *et al.* 2002). Other science goals are to attempt to identify the termination of the hydrogen burning MS and hence set the location of the brown dwarf boundary for metal–poor stars, establish the MF in the cluster down to very low masses and use the cluster WDs to extend the MF beyond the cluster turnoff, investigate the binary frequency in the cluster both through the location of stars in the CMD and via variability, explore for planets through stellar occultations, and examine the background bulge and inner halo populations (Rich *et al.* 2002, in preparation) and compare it with that of the cluster.

2. The Data and Its Reduction

The complete data set consists of 15×2600 sec exposures in F555W, 9×800 sec in F814W (1995 – part of GO 5461 from cycle 4 – see Richer *et al.* 1995, 1997; Ibata *et al.* 1999) together with 98×1300 sec in F606W and 148×1300 sec obtained in F814W (2001 – GO 8679 in cycle 9). All images were secured with the same roll angle in the same field of M4 located at about 6 core radii from the cluster center. We also processed and reduced the small set of F814W images from GO 8153 but in the final reductions they were not used.

M4 has an ecliptic latitude of $\sim 6^{\circ}$ and in late January when the first frames were taken the angle between the Sun and M4 was only slightly more than 60°. This produced some excess scattered light in our frames from zodiacal light. As time progressed during the 67 days over which the data were secured, the Sun angle increased and the situation improved. The net effect of the slightly higher background was to reduce our limiting magnitude by about 0.2 mags.

The new images as well as the earlier frames were preprocessed according to the recipe given in Stetson *et al.* 1998. The DAOPHOT (Stetson 1987) suite of programs was then used to find bright stars ($> 5\sigma$ detections above the sky noise) on individual frames, and photometry for these stars was obtained using the ALLSTAR program. ALLSTAR photometry was matched between frames using DAOMASTER producing a file containing the transformations between the frames.

The individual frames were then transformed to the coordinate system of the first new epoch frame using the MONTAGE2 program. Once the frames were all on the same coordinate system, those *corresponding to a particular epoch and filter* were averaged together with pixel rejection – the n highest pixels being rejected to eliminate cosmic ray contamination. From the HST WFPC2 Manual the mean number of pixels on a given chip affected by a cosmic ray hit in an 1800 sec exposure is about 20,000. Hence in a stack of N×1300 sec exposures we expect 0.02257N pixels at a given position to have suffered a hit. Taking the dispersion to be $\sqrt{0.02257N}$ and using 5σ rejection we find that in combining the 98 F606W images the highest 7 pixels should be rejected while for the 148 F814W images we should eliminate the highest 9. Statistically this approach is superior to a median of the frames, which is equivalent to a mean of 2/3 of the number of frames, whereas in our procedure we used 93% of the images in constructing the mean.

For each chip there are 4 combined frames, $\mathrm{V_{new}}$, $\mathrm{V_{old}}$, $\mathrm{I_{new}}$ and $\mathrm{I_{old}}$. These 4 frames are all on a common coordinate system. The new data is deeper than the old data, particularly in F814W, so a starlist was generated for each chip using DAOFIND on the $\mathrm{I_{new}}$ and $\mathrm{V_{new}}$ frames. We then (1) visually inspected each object in the list and rejected those objects that corresponded to detections of non-astronomical sources (such as diffraction spikes), (2) subtracted a spatially smoothed copy of the image from the image itself and inspected this image for missed stars, and finally (3) combined the 2 lists into our final starlist.

For each chip within the 4 frames the stars were photometered using ALLSTAR with the starlist as input. ALLSTAR fits a PSF to each object in the starlist and does recentering so as to achieve the best fit. Note that the ability of ALLSTAR to recenter is essential as this allows shifts between stars on the frames to be measured which is critical when applying the starlist from the new frames onto the first epoch images as the proper motion of the cluster relative to the background amounts to about 1 HST pixel over the 6 year time baseline. Using stars found in all 4 data sets, the parameters dx ($\mathrm{x_{new} - x_{old}}$) and dy ($\mathrm{y_{new} - y_{old}}$) were defined. A proper motion displacement (PMD) dx vs dy plot was made which separated almost all the objects into 2 distinct groups with their centers differing by about 1 HST pixel.

In registering the frames we used all reasonably bright stars in the field. However, as the cluster is moving with respect to the field stars (largely in the Galactic inner halo) there was some contamination from non-cluster stars even though cluster stars dominated the solution. To ensure that the individual frames were registered *on* the cluster stars, we selected only those within a radial distance of 0.5 pixels from the major clump in the PMD diagram. These are the cluster stars. We then re-reduced these stars on the four individual frames with ALLSTAR and matched them with the DAOMASTER program. To compensate for distortions in the HST optics, we used a 20-term transformation equation. This is in lieu of but equivalent to applying the Trauger *et al.* 1995 corrections. The new transformation file was thus built using only cluster stars which move insignificantly relative to each other as the observed cluster velocity dispersion is 3.5 km/s (Peterson *et al.* 1996), which amounts to a total internal mean motion of about 0.02 pixels over the 6 years.

We used this new transformation equation to again register the frames and to improve astrometric accuracy, we expanded the pc pixels by a factor of 2 and the wf pixels by a factor of 3 using MONTAGE2. This process is similar to "drizzling" (Fruchter & Hook 2002). The individual frames were then averaged together with high pixel rejection as previously described. It was on these combined, expanded frames that the final photometry was carried out using ALLSTAR. No charge transfer corrections were made as the high background and the uniform distribution of the faint stars across the chips suggested that this was not a serious problem on these images.

The resulting PMD diagram (Figure 1) separates cluster stars from the field population rather cleanly; this separation is essentially perfect if we restrict ourselves to the brighter stars. The clump of non-cluster stars in the PMD diagram clearly has a larger dispersion than that of the cluster; with an internal velocity dispersion of only 0.02 pixels in 6 years, motions within M4 are unresolved to our level of precision. If the field population were due solely to inner halo stars lying near the tangent point with a typical halo velocity dispersion of $\sim$ 110 km/sec, we would expect a PMD dispersion of 0.175 pixels ($R_0 = 8$ kpc). For stars in the V magnitude range 21 to 26, the measured PMD dispersion for the cluster is 0.082 pixels ($0''.0082$) which we take as our positional measurement error (confirmed by simulation) while the field clump has a dispersion of 0.277 pixls ($0''.0277$). Subtracting the cluster measurement in quadrature gives a field dispersion of $0''.0265$, considerably larger than expected. The field clump evidently does not consist solely of inner halo stars at 8 kpc. A complete discussion of this population will be given in Rich *et al.* (2002, in preparation).

In the lower two sections of Figure 1 we display the CMDs for data in different areas of the PMD diagram. The data were transformed to Johnson V and Kron-Cousins I using stars measured in GO 5461 and calibrated with ground-based data as discussed in Richer *et al.* 1997. This resulted in a significant color term in the transformation of F606W to Johnson V. The left panels plot all the objects (stars as well as possible galaxies) measured from all 4 chips with no rejection criteria. The central panels isolate the cluster stars – objects within 0.5 pixel in radius ($0''.05$) of the mean motion of the cluster. Our simulations suggest that $< 1\%$ of cluster stars will have measured PMDs outside this radius. From these CMDs we also rejected objects with $\chi > 10$, sharp > 4 as returned by DAOPHOT and those which were obvious galaxies based on a visual inspection. These are very benign cuts that exclude only clearly pathological objects. The right panels contain the inner halo stars, again isolated with a 0.5 pixel radius circle centered on their mean motion with respect to the cluster. Any faint unresolved galaxies will appear in this CMD.

3. The Approach to the Hydrogen-Burning Limit

M4 is ideally suited for studies of the pop II hydrogen burning limit, by virtue of its proximity and relatively (amongst globular clusters) low concentration. From the ground, the best attempt to study the lower main sequence was made by Kanatas *et al.* 1995, who were limited primarily by field star contamination. Deep images using NICMOS and WFPC on HST allowed Pulone, de Marchi & Paresce 1999 to probe estimated masses down to $\sim 0.15 M_\odot$, but with poor statistics. A second epoch of HST observations allowed Bedin *et al.* 2001 to separate cluster members from background stars using the cluster proper motion, with the faintest cluster members measured at F814W $\sim$ 24.5 with masses near $0.1 M_\odot$. Bedin *et al.* note that the lack of detections in their last magnitude bin may herald the 'steep plunge' they expect to correspond to the hydrogen burning limit, but admit that this result is statistically weak. The considerably deeper observation described above allows us to examine this question in more detail.

Inspection of Figure 1 shows that, while there is indeed a paucity of stars at $V > 27.5$, $I > 23.8$, there does remain a trail of potential MS stars extending redwards, almost to V = 30. These stars are present even with very restrictive proper motion cuts and have a high probability of cluster membership (Figure 2) so we are convinced that the LF does not have an abrupt termination. Indeed, there is little reason to expect that it will as the current generation of low mass MS models (Baraffe *et al.* 1997, Cassisi *et al.* 2000, Montalban *et al.* 2000) all predict large changes in luminosity and color with very small changes in mass near the hydrogen burning limit. Hence the approach to the hydrogen-burning mass limit should be characterised by an extended LF, such as is indeed seen in M4.

The least luminous MS stars observed in M4 are significantly fainter than any other known subdwarf at this metallicity (Leggett *et al.* 1998b; compare with LHS 1742a and LHS 377). An immediate consequence is that there should be correspondingly faint red subdwarfs in the field waiting to be discovered, although they will be rare. For every field subdwarf in the range $7.5 < M_V < 15$, there should be ~ 0.02 subdwarfs with $15 < M_V < 17.4$, or less than 1 in 30,000 of all stars in the Solar neighbourhood.

There is also a small sample of apparent cluster members located between the cooling sequence and the MS, and some are fainter in V than even the least luminous white dwarfs detected. It is possible that these are field objects with proper motions similar to the cluster. If they are indeed cluster members, they could be low luminosity He WDs in binaries with extremely low mass MS stars. Indeed, such objects are predicted to be the remnants of cataclysmic variables currently accreting at very low rates (Townsley & Bildsten 2002). Alternatively, these may indicate a range of colors for pop II stars near the hydrogen-burning limit, since low mass, low metallicity stars can be quite blue (Saumon *et al.* 1994).

4. The Cluster Mass Function

First we must note, as have other authors, that the derivation of a MF from the LF is an uncertain procedure because the theoretical models for low temperature stars of this metallicity (Baraffe *et al.* 1997; Cassisi *et al.* 2000, Montalban *et al.* 2000) do not fit the lower MS very well. With this caveat, we generate the cluster MF (Figure 3) by constructing the LF (number of cluster stars per half magnitude interval along the MS), correcting for incompleteness by adding stars of known magnitude and color into the frames, rereducing them, and converting luminosities to mass using the models of Montalban *et al.* The resulting MF rises very slowly to low masses, with a formal slope $\alpha = 0.75$ ($N(m) \propto m^{-\alpha}$, Salpeter $\alpha = 2.35$). A χ^2 fit using the models of Montalban *et al.* finds that slopes of $\alpha = 0.55$ –1.05 are acceptable at the 99% confidence level (a tighter constraint will be possible when better lower MS models are available). Thus, there is no evidence that the MF turns over, even to the lowest masses we detect ($\sim 0.09 M_\odot$). This assertion is more solid than might appear from the uncertain model fitting. The total number of stars fainter than $I \sim 21$ (brighter than this the models do fit the data) is consistent with the expectations based on the extrapolated mass function down to $M \sim 0.09 M_\odot$, regardless of the M-L relation.

The detection of the white dwarf population also allows us to constrain the MF slope above the cluster turnoff as discussed in Richer *et al.* 1997. The completeness-corrected WD counts are 602 to $V = 30$. The detected 570 MS stars between $0.09 M_\odot$ and $0.65 M_\odot$ (upper limit due to saturation) imply 1219 white dwarfs if the slope $\alpha = 0.75$ extends all the way through the turnoff mass ($0.8 M_\odot$) to the expected upper limit for white dwarf progenitor masses ($8 M_\odot$). Thus, we find a factor two less than expected. However, if the mass function slope is at the steep end of the acceptable range found above, then we predict 584 WDs, in agreement with the observed numbers. Thus, the extant data are (just) consistent with a single mass function slope extending from $0.09 M_\odot$ to $8 M_\odot$.

There are obviously other possible interpretations as well.

- If the MF slope on the lower MS is indeed close to $\alpha \sim 0.75$, then the mass function slope must steepen at higher masses. This is often seen in clusters. However, the white dwarf counts are far above that expected if the global M4 IMF of Pulone et al. 1999 is adopted. They propose $\alpha \sim 2.4$ above the turnoff mass, which would predict a paltry 264 white dwarfs. Furthermore, if M4 has undergone significant mass segregation as they suggest, this number would be even smaller. If the MF has a break at $0.8 M_\odot$, then the white dwarf count restricts $\alpha \sim 1$ above the break.
- If there is a significant fraction of the cluster white dwarf population which possess pure He atmospheres, they will have cooled beyond our detection limit (Hansen 1999)

and will not be included in the above census. If this population comprised 50% of all cluster white dwarfs, that would allow a continuous power law $\alpha = 0.75$ from $0.09M_\odot$ to $8M_\odot$.

- In estimating the number of WDs expected for MS MF slopes as flat as we have found, the upper mass limit for white dwarf progenitors becomes important. We predict the correct number of white dwarfs for the $\alpha = 0.75$ slope if this mass is as low as $3M_\odot$.

Although there are several possible conclusions, with a slope above the turnoff of $\alpha \sim 1$, we can naturally account for all the white dwarfs seen. This would suggest the overwhelming population of cluster white dwarfs have hydrogen-rich atmospheres and would be a clear indication that we have seen the termination of the WD cooling sequence in M4.

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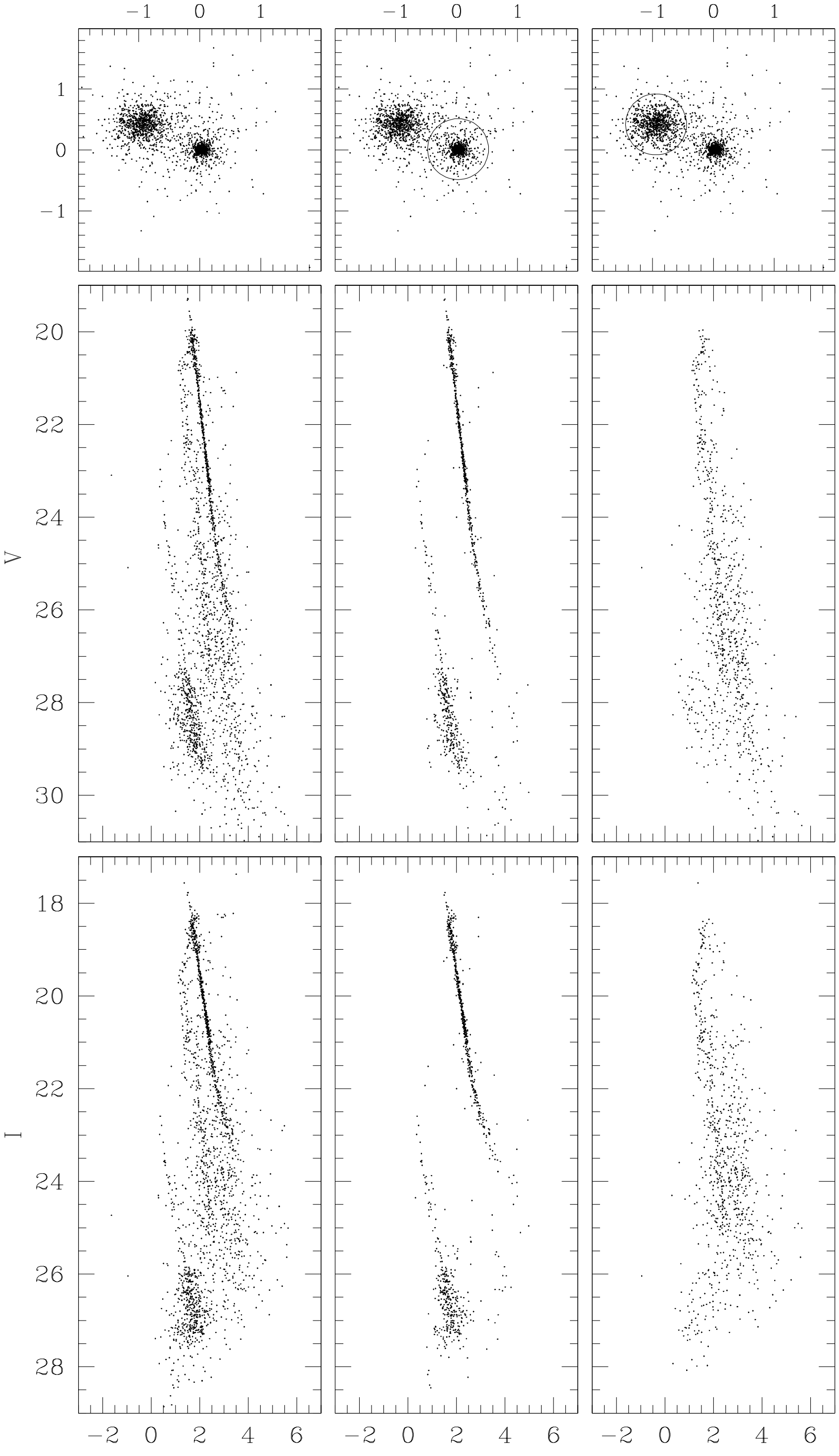
Fig. 1.— Upper – The PMD diagram centered on the cluster. Each unit is 1 HST pixel. Middle – The V, V−I CMDs for objects selected by PMD. The central panel is for M4 using stars with PMDs within $0\farcs05/6$ yrs of that of the mean motion of the cluster. Bottom – The I, V−I CMDs. In the center, the hook to the blue in the WD cooling sequence of M4 is as predicted by theory and is caused by H_2 opacity.

Fig. 2.— Measured PMD over 6 years from the centroid of the cluster as a function of I magnitude for all objects. The red dots are those objects with $V - I > 4.0$ and illustrates that there is a component of extremely faint red stars that are very likely cluster members.

Fig. 3.— Upper – The M4 MS LF corrected for incompleteness and showing these corrections for both MS and WD stars. Lower – The M4 MS MF with power law slope $\alpha = 0.75$ indicated.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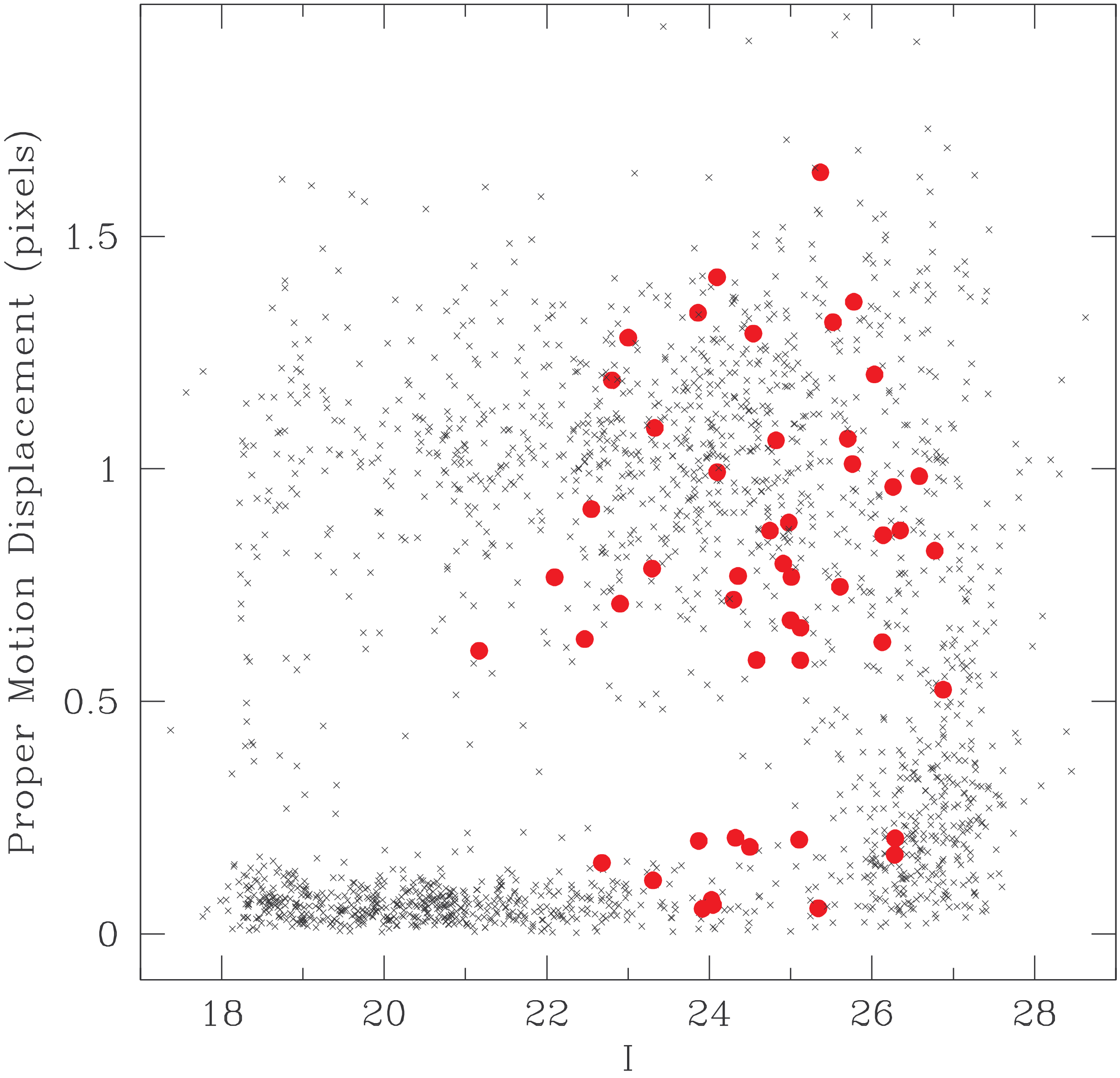
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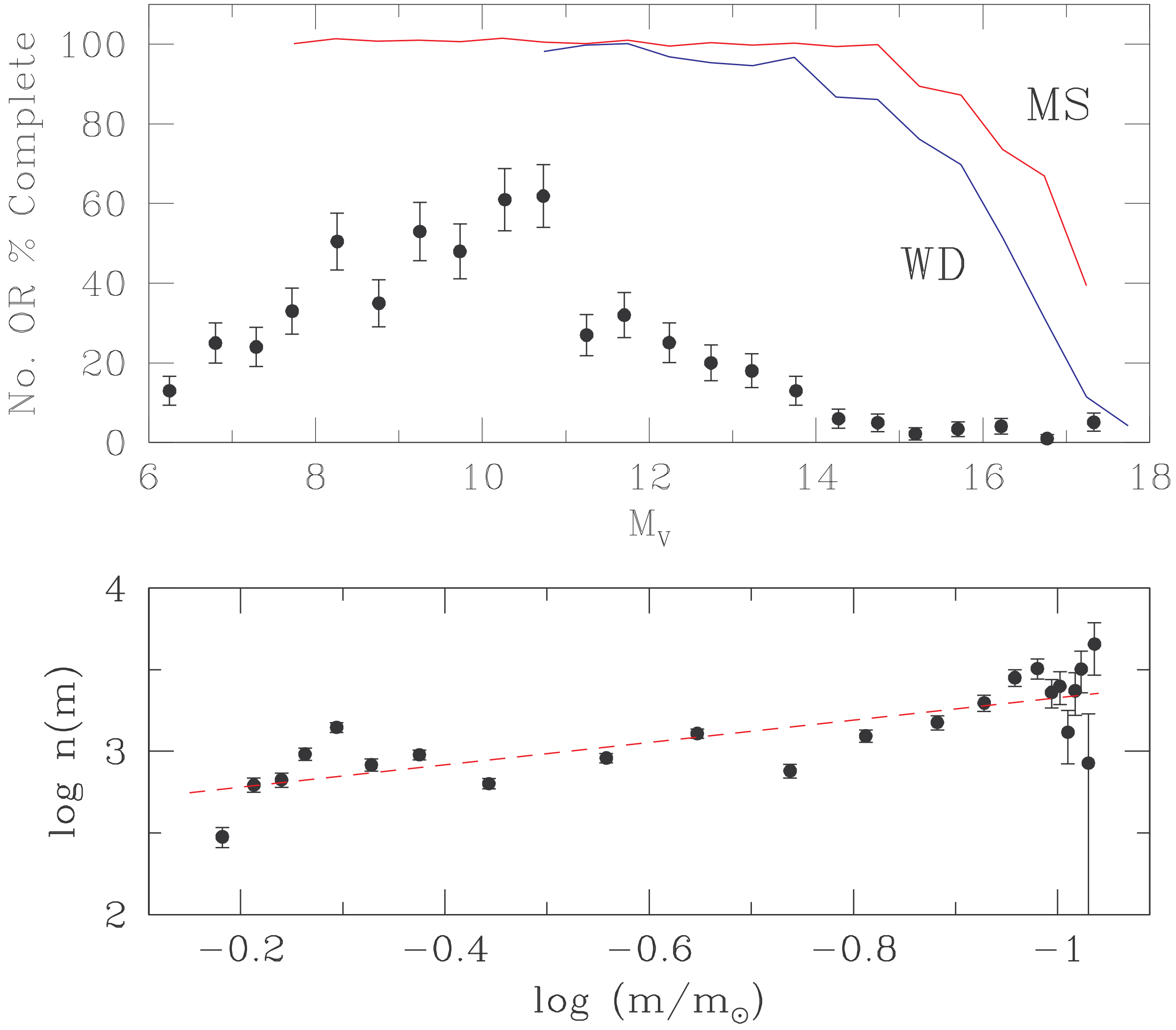
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