Cume #318 **16 September 2006**

The following questions address the paper "Probing the Faintest Stars in a Globular Star Cluster" which recently appeared in Science (H. B. Richer, *et al.*, 2006, *SCIENCE*, **313**, 936). Most can be adequately answered with a few lines of text, and perhaps and equation or two, so please be reasonably brief. The questions carry equal weight for grading purposes.

1. Why did the authors chose this particular globular cluster for this investigation? Why not select another globular cluster, another kind of cluster - or simply observe field stars?

2. What are the nuclear reactions which halt contraction of objects with masses just above the 0.8 solar mass "brown dwarf limit" as they approach the main sequence? Why are these reactions able to (sometimes) halt the contraction? (Hint: Why is the object contracting in the first place?)

3. Why is the mass range "from about 1 through 7 solar masses" the only part of the stellar mass spectrum considered as progenitors of the white dwarfs in NGC 6397?

4. What, exactly, is the quantity F814W? What is (F606W - F814W)? What is the range of relative brightness of the stars shown in Figure 2?

5. The extreme narrowness of the main sequence in the F814W direction - which becomes particularly apparent in the vicinity of (F606W-F814W) ~ 2 - strikes me as a rather "remarkable feature" of Figure 2B; the width is less than 0.2 in F814W. Why do I find this surprising? What does it suggest? (Hint: I would have found an intrinsic dispersion much bigger than 0.75 magnitude puzzling as well.)

6. The authors note that these observations, together with theoretical models for white dwarfs, can be used to determine the age of a cluster. How might you accomplish this without those models, using only the data given in this paper?

7. Using the information given in the paper estimate the proper motion and transverse velocity of NGC 6397. Is the value you get for the latter reasonable?

8. The authors suggest that a population of faint metal-poor stars is "awaiting discovery in the halo of the galaxy." On what basis do they suggest that there is an undiscovered population? Are you convinced? See page 938. Column 2, line 8-10,

9. What is meant by "electron degeneracy"? It is invoked as being responsible for supporting both "failed" brown dwarfs and the white dwarf end products of stellar evolution.

P, T, M, Po.

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Probing the Faintest Stars in a Globular Star Cluster

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NGC 6397 is the second closest globular star cluster to the Sun. Using 5 days of time on the Hubble Space Telescope, we have constructed an ultradeep color-magnitude diagram for this cluster. We see a clear truncation in each of its two major stellar sequences. Faint red main-sequence stars run out well above our observational limit and near to the theoretical prediction for the lowest mass stars capable of stable hydrogen burning in their cores. We also see a truncation in the number counts of faint blue stars, namely white dwarfs. This reflects the limit to which the bulk of the white dwarfs can cool over the lifetime of the cluster. There is also a turn toward bluer colors in the least luminous of these objects. This was predicted for the very coolest white dwarfs with hydrogen-rich atmospheres as the formation of H_2 and the resultant collision-induced absorption cause their atmospheres to become largely opaque to infrared radiation.

When stars are born, they contract under gravity, increasing their central temperatures and densities. If a star is massive enough, at least 0.08 that of the Sun (80 times the mass of Jupiter), the center will eventually get hot enough to allow self-sustaining nuclear energy generation at a level sufficient to halt the contraction. For lower mass objects, the contraction is halted instead by electron degeneracy, the quantum mechanical repulsion between electrons in dense media. For these "brown dwarfs," the rate of energy generation never grows large enough to be self-sustaining, and they fade away within a billion years (*1*). On the other hand, for low-mass stars just above the brown dwarf mass limit, the balance between gravity and thermal equilibrium is long-lived, and these stars are able to shine for much longer than the current age (13.7 billion years) of the universe (*2*). The sharp division between transient and effectively infinite lifetime populations is termed the hydrogen-burning mass limit and is a cornerstone of stellar evolutionary theory. However, because of the faintness of the stars just above the limit, this edge has not previously been solidly identified in any old stellar population such as globular clusters or halo field stars.

At the other end of the stellar mass spectrum, stars with masses ranging from about 1 through 7 solar masses consume their nuclear fuel on a time scale shorter than the age of the universe, burning their original hydrogen, to carbon and oxygen, ejecting their outer layers, and becoming white dwarfs. These stellar remnants are also supported by electron degeneracy pressure and slowly cool over time as they radiate their reservoir of thermal energy left over from the previous stages of nuclear burning. The accompanying slow fading, at approximately constant radius, traces out the so-called white dwarf cooling sequence in the color-magnitude diagram (CMD). At faint magnitudes, this sequence is expected to end, with the magnitude of the cutoff indicating the luminosity to which the oldest white dwarfs have faded. With the aid of theoretical models, this luminosity can then be used to derive the age of the cluster (*3*, *4*).

The white dwarf cooling sequence is expected to turn back to the blue at faint magnitudes (*5*–*9*). As white dwarfs with hydrogen-rich atmospheres cool below temperatures of 4000 K, they exhibit the collision-induced absorption (CIA) of molecular hydrogen (*10*). CIA is strongest at near-infrared wavelengths, which suppresses the flux near 1 μm (*11*) and causes the optical colors to become bluer as the star cools, rather than redder, as might be expected from a blackbody. CIA arises because hydrogen molecules can form in these cool atmospheres. Being symmetric, H_2 does not have a dipole moment and will only very weakly absorb radiation via quadrupole transitions (*10*). A dipole moment may be induced, however, during an H_2-H_2, H_2-H, or H_2-He collision (*12*), leading to CIA. The stars continue to get bolometrically fainter and cooler as they evolve on the blueward track in the CMD known as the blue hook. The spectral signature of CIA has been seen in a few individual field white dwarfs (*13*–*15*), but never as a feature in the cooling sequence of a stellar cluster. The expected cluster CIA signature is a blue hook in the cooling sequence. We note that this is a temperature effect, seen at faint magnitudes, and that it is distinct from the feature observed in the open cluster NGC 6791 (*16*). The latter feature occurs in younger populations and is a consequence of the smaller radii and slower cooling of more massive white dwarfs at early times, as shown in figure 17 of (*17*).

Imaging data. In an attempt to locate the limits of both the faint main-sequence star population and the faint white dwarf population, we used the Hubble Space Telescope (HST) to obtain images of the globular star cluster NGC 6397 located in the southern constellation Ara. It is seen projected in the direction of the galactic center, at a distance of about 8500 light-years from Earth (*18*), and its stars have a heavy-element content that is ~1% that of the Sun (*19*). It was discovered by Abbé Nicolas Louis de Lacaille during his sojourn at the Cape of Good Hope in 1751–1752; in his original catalog, it bears the name Lacaille III.11. It was the 12th such cluster discovered. We imaged a single field in NGC 6397 with the Advanced Camera for Surveys (ACS) on the HST for a total of 126 orbits (4.7 days) to characterize the faintest globular cluster stellar populations. Our observations were carried out 5 arc min southeast of the cluster core. They overlap preexisting Wide Field Planetary Camera 2 (WFPC2) images that we used to select, by common proper motion (angular motion in the plane of the sky), a clean sample of cluster stars largely devoid of galactic foreground and background stars. The exposures were taken through two filters, F606W and F814W, where the number indicates the central wavelength of the filter in nanometers.

The data set consists of 252 exposures totaling 179.7 ksec in F814W and 126 exposures totaling 93.4 ksec in F606W. This 2:1 ratio was chosen because the primary science goal of the program was exploration for the coolest white dwarfs. If cool white dwarfs do indeed turn blue at faint magnitudes (*5*–*9*), they will be very faint on the longer wavelength images, thus requiring increased exposure time to detect them. To find the faintest possible sources, we scoured each image for indications of where the faintest stars might be located. The most we could hope for from the very faintest ones is that they would push their central pixels up above the noise in some significant number of images. We studied the noise in the images via artificial star tests, and we concluded that a detection in 90 out of 252 F814W images constituted a 3σ detection above the background.

Figure 1 is an image of part of our field that was constructed by combining the exposures in

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the two filters. The insets provide expanded views of two stars at the extremities of stellar evolution: the least luminous hydrogen-burning cluster star observed (bottom) and a white dwarf that is cool enough to lie in the blue hook part of the cooling sequence (top).

Cluster CMD. We constructed a CMD (Fig. 2A) from these data, including all sources that (i) generated local maxima in at least 90 out of 252 F814W images, (ii) were the most significant sources within 7.5 ACS pixels, and (iii) passed morphology tests indicating that they are point-like objects. In this diagram, brighter stars have small values of the F814W magnitude and red stars will have larger positive (F606W − F814W) colors. Some unresolved faint blue galaxies likely remain in the sample bluer than (F606W − F814W) = 1 and fainter than F814W = 27. To estimate the photometric errors for white dwarf stars, we used measurements of artificial stars of known magnitude inserted into the individual exposures and recovered by our finding and measuring algorithms. In addition, we considered the completeness for stars as a function of the F814W magnitude—that is, the fraction of stars that we recovered in the ACS images in artificial star tests. The completeness is based solely on the recovery fractions in the F814W data and hence applies equally well to both white dwarfs and main-sequence stars. Completeness fractions in excess of 50% are normally considered acceptable.

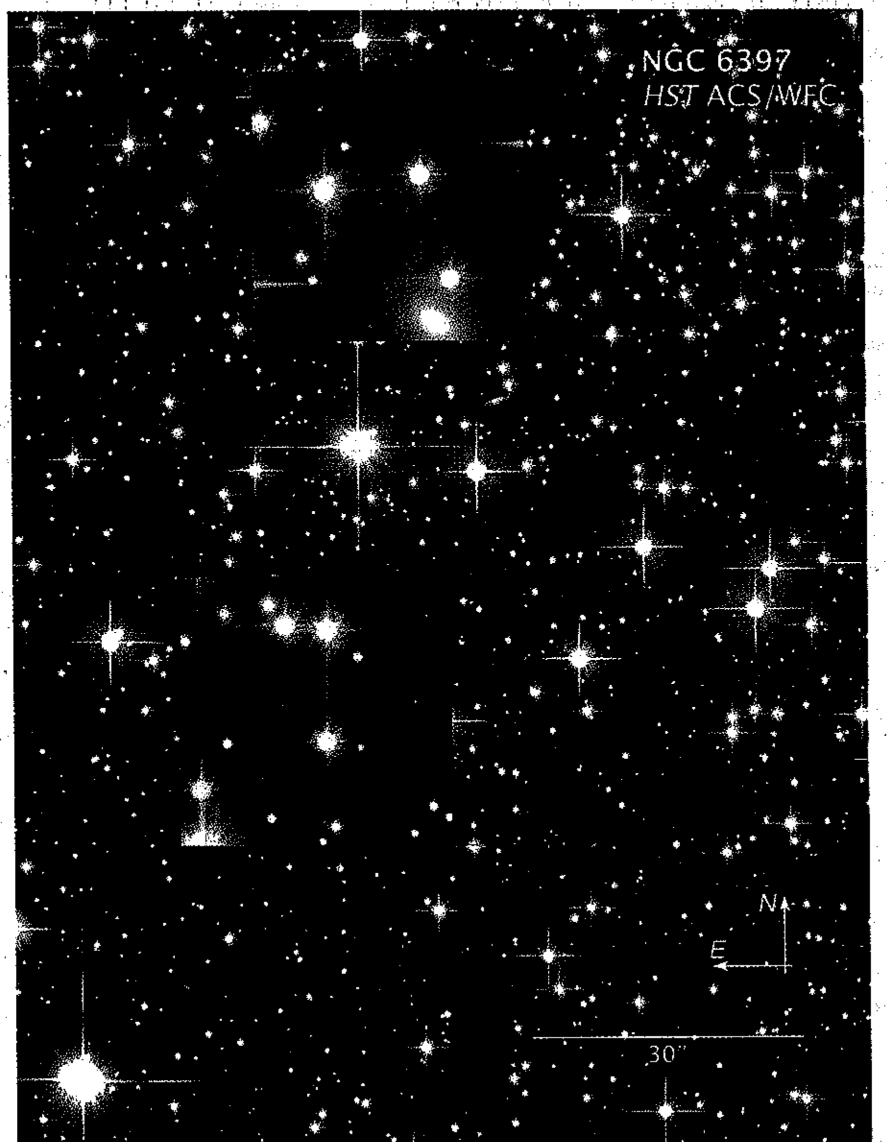

Fig. 1. A section of the observed field in NGC 6397 covering 94 arc sec by 127 arc sec. This is 29% of the entire field of our observations. Directions on the sky and a scale bar are shown at the lower right. The image is a composite of exposures from the HST ACS wide-field camera in F606W and F814W. The insets (each 10 arc sec by 10 arc sec) show detail for the faintest hydrogen-burning star observed in the cluster (top) and a white dwarf along the blue hook part of the cooling sequence (bottom). Although the field is in a globular star cluster with many bright stars, the ACS has such a tight point spread function, with relatively little scattered light, that it is still possible to see faint external galaxies right through the cluster.

Figure 2A is dominated by a narrow continuous cluster sequence spanning at least 14 magnitudes in the F814W filter. The sequence extends from a sparse giant branch at the brightest F814W magnitudes, through the main-sequence turnoff near F814W = 15.7, and down the main sequence to faint objects, with a possible termination in a cloud of field stars near F814W = 24. The turnoff region corresponds to stars that have recently completed hydrogen burning in their cores. They will shortly evolve into red giants, a phase of evolution lasting about 100 million years, before they eject their atmospheres and become white dwarfs. The scatter around this narrow sequence is produced by stars not associated with the cluster. These are stars from the galactic disk and bulge that are found along the line of sight to NGC 6397. This population is large because of the low galactic latitude (−12°) of NGC 6397.

The most novel feature of the diagram, however, is the white dwarf cooling sequence, which begins at about F814W = 22.5 and extends to F814W = 27.2, where it then "hooks" toward the blue. The sequence appears to be largely truncated fainter than F814W = 27.8. This truncation reflects the limit to which the bulk of the hydrogen-rich white dwarfs can cool over the lifetime of the cluster. For this reason it will be a powerful diagnostic in determining the age of NGC 6397. However, this truncation does not necessarily mean that there are no white dwarfs in the cluster fainter than this limit. Over a long period of time, both massive white dwarfs (those with masses in excess of about 0.8 that of the Sun) and those with helium-rich atmospheres cool more quickly and to fainter magnitudes than do white dwarfs of modest mass (0.5 to 0.6 solar masses) with hydrogen-rich atmospheres. As a consequence of electron degeneracy, more massive white dwarfs have smaller radii and hence larger densities. They will thus develop a crystallized core earlier than low-mass white dwarfs, causing them to enter a regime known as Debye cooling before the lower mass ones do. In this phase of evolution, the star effectively loses its ability to store thermal energy and it cools very rapidly. Because helium does not form molecules (which would have a vibrational mode), white dwarfs with pure helium atmospheres do not suffer from CIA. Their atmospheres are thus less opaque to infrared radiation and they cool rapidly. Hence, both massive and helium-rich white dwarfs may have cooled to below our observational limit.

We examined the details of the CMD further by analyzing the stars whose proper motions match that of the cluster (Fig. 2B and Fig. 3). Preexisting WFPC2 images, which were used to proper motion–clean the data, overlap only 60% of the area of the ACS field and are much shorter in exposure time (F814W exposure times of 3960, 7440, and 5200 s in each of the 1994, 1997 and 2001 data sets, versus 179.7 ksec with the ACS in 2005) so that their utility, particularly for the very faintest stars, was limited. Distinguishing between cluster and field stars is a serious issue for stars along the main sequence as well as those in the white dwarf region. The main-sequence stars become very red at faint magnitudes, so they may be found on the F814W images but could be unmeasurable on the bluer F606W frames. For the white dwarfs, if they do indeed become bluer as they cool (*5–9*), we might expect to lose them on the F814W frames. Nonetheless, the major features are preserved and are much cleaner in Fig. 2B than in Fig. 2A. The main sequence is now seen to continue to F814W ~ 26.0 at (F606W – F814W) ~ 4.0. An F814W magnitude of 26.0 and a F606W magnitude of 30.0 correspond to absolute magnitudes of 13.6 and 17.4, respectively. These absolute magnitudes are more than a full magnitude fainter than the faintest known metal-poor ("population II") field stars (*20, 21*), which suggests that there remains a population of extremely dim metal-poor stars awaiting discovery in the halo of the galaxy.

The cluster main sequence has two remarkable features: one at F814W ~ 24, where the number counts of stars decline rapidly [noted by (*22*)], and another at F814W ~ 26, where the main sequence appears to terminate. This latter feature is not caused by incompleteness (Fig. 3). Except for a few stars that scatter well away from the main-sequence locus (all these are also outliers in the proper motion distribution, so they are likely interlopers from the field population), there appears to be a complete lack of cluster main-sequence stars fainter than F814W = 26. The presence of an extensive white dwarf population as faint as F814W = 27.8, as well as numerous faint field stars, shows that if a significant population of main-sequence stars fainter than F814W = 26 were present, we would have found it.

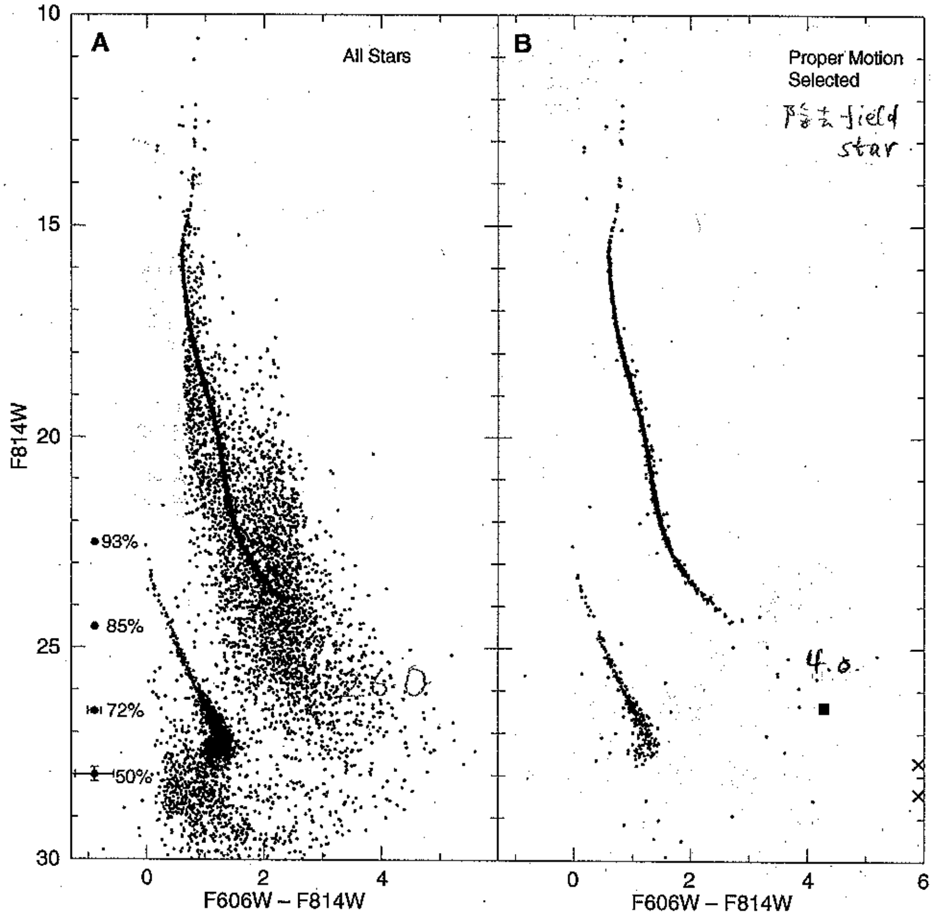

Fig. 2. The CMD of NGC 6397 (**A**) without proper motion selection of cluster members, and (**B**) after cleaning the data with the use of proper motions to exclude noncluster stars in the galactic disk and bulge from the sample (see also Fig. 3). Most of the faint galaxies and artifacts have been removed from (A) by requiring that the found objects pass certain morphological tests. The 1σ photometric errors as a function of magnitude are indicated for white dwarfs by the error bars at F814W = 22.5, 24.5, 26.5, and 28.0, as well as the percentage of stars (either white dwarfs or main sequence) found in the ACS images at each of these magnitudes from artificial star tests. In (B) the cluster main sequence appears to terminate at F814W = 26, (F606W – F814W) = 4. The few scattered objects at lower luminosity are at the extremes of the proper motion selection criteria and are likely interlopers from the large field population. The two X's to the right indicate the F814W magnitudes of the stars that passed the proper motion cuts but whose F606W magnitudes were not measured. The solid square is the location of the hydrogen-burning limit for one particular set of theoretical models (*23, 24*).

Proper motions. We quantified this result by examining the proper motion distribution for faint red and blue stars (Fig. 3). NGC 6397 is moving relative to the field stars. Over the course of 10 years since the first archival data were taken, the cluster stars have moved by almost 3 ACS pixels with respect to the bulk of those in the field. A displacement this large is trivial to measure, provided we can find the star in the archival data. Figure 3 displays the proper motions for all objects with respect to the cluster as a function of F814W magnitude. The proper motion cuts we made to select cluster stars are shown in Fig. 3A; these stars are all to the left of the red line, which is set by fitting a Gaussian function to the total proper motion distribution in bins one magnitude wide and selecting those stars that lie within two standard deviations from the mean. The remaining plots are proper motions along the detector axes for stars redder than (F606W – F814W) = 1.5 (Fig. 3, B to D) and for blue stars with (F606W – F814W) < 1.5 (Fig. 3E). The circle shown in each plot is the proper motion cut appropriate to that magnitude. The circle has a radius of 0.5 ACS pixels in Fig. 3B and 1.3 pixels in Fig. 3, D and E. By contrast, proper motion errors in x and y range from 0.05 pixels at F814W = 22 to 0.6 pixels at F814W = 26. It is clear that clumps corresponding to cluster stars are seen in Fig. 3, B and C, but that no concentration is seen for red main-sequence stars with F814W > 26 (Fig. 3D). This coincides with the impression in Fig. 2B that there are no obvious cluster stars fainter than this limit. Figure 3E illustrates the displacements for stars with (F606W – F814W) < 1.5 and F814W > 26, which includes cluster white dwarfs, blue field stars, and unresolved blue galaxies. Clearly, there is a sizable component of stars moving with the cluster at these faint magnitudes (the white dwarfs), so that the deficiency seen for the main-sequence stars is real and not due to incompleteness.

Hydrogen-burning limit. The apparent termination of our observed main sequence lies close to the predicted hydrogen-burning limit (Fig. 2B, solid square); the lowest mass star capable of stable nuclear fusion of hydrogen in its core is 0.083 solar masses at the low heavy element abundance of NGC 6397 (*23, 24*). We caution, however, that different models may yield different results. At masses just above the hydrogen-burning limit, the relation between the mass and luminosity of a star is very steep; an extremely small change in mass results in a large

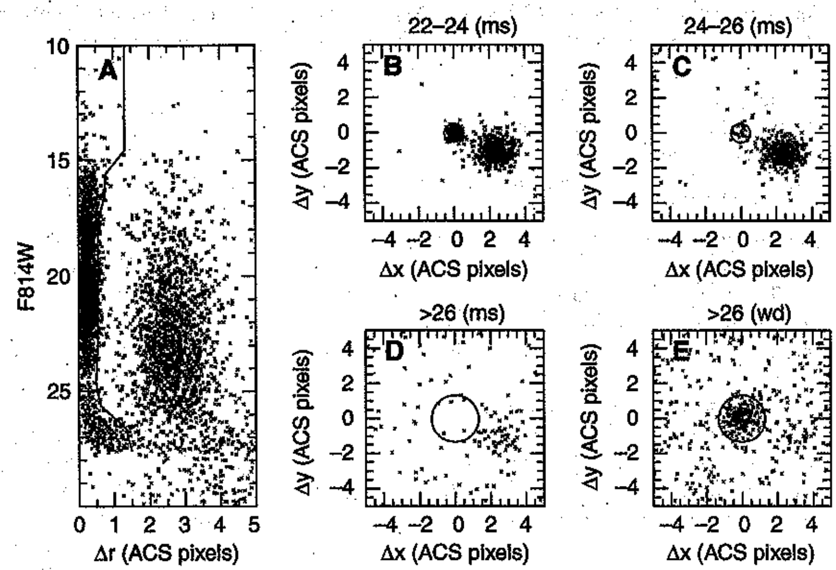

Fig. 3. (**A**) The F814W magnitude plotted against total stellar proper motion displacement Δr (scaled to 10 years) with respect to the cluster. The units are ACS pixels that project to 0.05 arc sec on the sky. The red line shows the selection criterion; all stars to the left of the line are considered to be cluster members. (**B** to **E**) Displacements in the x and y directions on the detector ($-x$ is approximately north; ms, main sequence; wd, white dwarf). The NGC 6397 stars are those in the tight clump at (0,0); the bulk of the field stars are located in the diffuse clump about 3 pixels away.

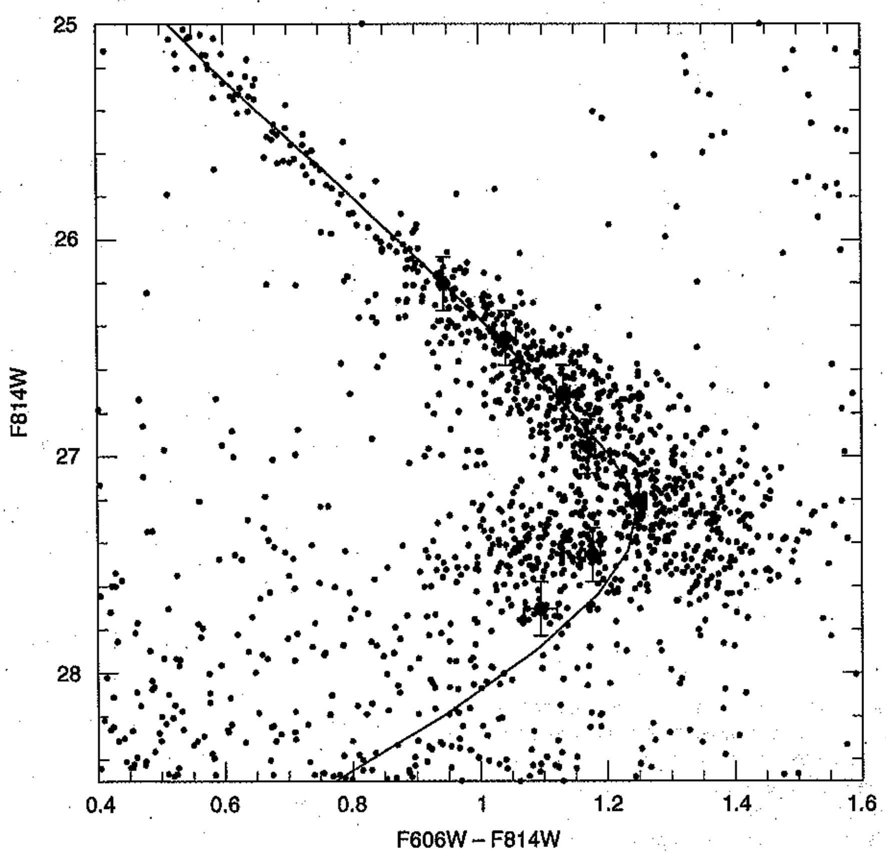

Fig. 4. The white dwarf region of the full CMD (i.e., not proper motion–cleaned) overlaid with the empirical cooling sequence (red dots with 1σ error bars) derived as described in the text. We use the full CMD here in lieu of the proper motion–cleaned one to avoid artificial truncation of the cooling sequence from losses of stars from the shorter exposure, earlier epoch data. The solid blue curve is a theoretical cooling sequence using the atmospheric models of Bergeron *et al.* (*7*) and a cooling model for 0.5 solar mass white dwarfs of Hansen (*6*).

change in luminosity. This is because at low masses, electron degeneracy pressure becomes important in supporting the star. The temperature no longer increases with increasing pressure as it does for a classical gas. This has th effect of decreasing the central temperature an hence the nuclear energy generation rate (*25*). As stars approach the hydrogen-burning limit in mass, we thus expect to see a steep decline in their number counts as a function of luminosity. This makes it highly improbable that any stars will be found at the hydrogen-burning limit.

Blue hook. The blue hook feature in the white dwarf cooling sequence remains after proper motion cleaning, leading us to conclude that we are indeed seeing the predicted CIA signature (*5*–*9*). We quantified the nature of the hook by deriving an empirical cooling sequence. We fit the observed color distribution in F814W magnitude bins of width 0.25 with a model of the dispersion in color determined from artificial star tests. This resulted in a relation between color and magnitude that is purely empirical and can be compared to any theoretical models of the cooling. In Fig. 4, we show the comparison between this relation and one particular theoretical cooling sequence. Note that there is indeed a blue hook in the empirical relation and that we see excellent agreement between this and the model curve. This concordance suggests that further detailed modeling of these cool white dwarfs will provide a strong constraint on the white dwarf cooling age of NGC 6397.

Final remarks. In 1984, the late Vitto Castellani and Vittoria Caloi suggested to the European Space Agency that HST be used to locate the end of the hydrogen-burning main sequence in the nearest globular star clusters. We believe that we have met this challenge. In addition, the blue hook and a truncation in the white dwarf cooling region have also been located. These features can now be exploited to learn more about the structure of low-mass stars, brown dwarfs, the original massive stellar component in globular clusters, white dwarf atmospheres and cooling, and ultimately the ages of these oldest known stellar populations.

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Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity

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Western United States forest wildfire activity is widely thought to have increased in recent decades, yet neither the extent of recent changes nor the degree to which climate may be driving regional changes in wildfire has been systematically documented. Much of the public and scientific discussion of changes in western United States wildfire has focused instead on the effects of 19th- and 20th-century land-use history. We compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it with hydroclimatic and land-surface data. Here, we show that large wildfire activity increased suddenly and markedly in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. The greatest increases occurred in mid-elevation, Northern Rockies forests, where land-use histories have relatively little effect on fire risks and are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.

Wildfires have consumed increasing areas of western U.S. forests in recent years, and fire-fighting expenditures by federal land-management agencies now regularly exceed US$1 billion/year (*1*). Hundreds of homes are burned annually by wildfires, and damages to natural resources are sometimes extreme and irreversible. Media reports of recent, very large wildfires (>100,000 ha) burning in western forests have garnered widespread public attention, and a recurrent perception of crisis has galvanized legislative and administrative action (*1*–*3*).

Extensive discussions within the fire-management and scientific communities and the media seek to explain these phenomena, focusing on either land-use history or climate as primary causes. If increased wildfire risks are driven primarily by land-use history, then ecological restoration and fuels management are potential solutions. However, if increased risks are largely due to changes in climate during recent decades, then restoration and fuels treatments may be relatively ineffective in reversing current wildfire trends (*4*, *5*). We investigated 34 years of western U.S. (hereafter, "western") wildfire history together with hydroclimatic data to determine where the largest increases in wildfire have occurred and to evaluate how recent climatic trends may have been important causal factors.

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Competing explanations: Climate versus management. Land-use explanations for increased western wildfire note that extensive livestock grazing and increasingly effective fire suppression began in the late 19th and early 20th centuries, reducing the frequency of large surface fires (*6*–*8*). Forest regrowth after extensive logging beginning in the late 19th century, combined with an absence of extensive fires, promoted forest structure changes and biomass accumulation, which now reduce the effectiveness of fire suppression and increase the size of wildfires and total area burned (*3*, *5*, *9*). The effects of land-use history on forest structure and biomass accumulation are, however, highly dependent upon the "natural fire regime" for any particular forest type. For example, the effects of fire exclusion are thought to be profound in forests that previously sustained frequent, low-intensity surface fires [such as Southwestern ponderosa pine and Sierra Nevada mixed conifer (*2*, *3*, *10*, *11*)], but of little or no consequence in forests that previously sustained only very infrequent, high-severity crown fires (such as Northern Rockies lodgepole pine or spruce-fir (*1*, *5*, *12*)].

In contrast, climatic explanations posit that increasing variability in moisture conditions (wet/dry oscillations promoting biomass growth, then burning), and/or a trend of increasing drought frequency, and/or warming temperatures have led to increased wildfire activity (*13*, *14*). Documentary records and proxy reconstructions (primarily from tree rings) of fire history and climate provide evidence that western forest wildfire risks are strongly positively associated with drought concurrent with the summer fire season and (particularly in ponderosa pine–dominant forests) positively associated to a lesser extent with moist conditions in antecedent years (*13*–*18*). Variability in western climate related to the Pacific Decadal Oscillation and intense El Niño/La Niña events in recent decades along with severe droughts in 2000 and 2002 may have promoted greater forest wildfire risks in areas such as the Southwest, where precipitation anomalies are significantly influenced by patterns in Pacific sea surface temperature (*19*–*22*). Although corresponding decadal-scale variations and trends in climate and wildfire have been identified in paleo studies, there is a paucity of evidence for such associations in the 20th century.

We describe land-use history versus climate as competing explanations, but they may be complementary in some ways. In some forest types, past land uses have probably increased the sensitivity of current forest wildfire regimes to climatic variability through effects on the quantity, arrangement, and continuity of fuels. Hence, an increased incidence of large, high-severity fires may be due to a combination of extreme droughts and overabundant fuels in some forests. Climate, however, may still be the primary driver of forest wildfire risks on interannual to decadal scales. On decadal scales, climatic means and variability shape the character of the vegetation [e.g., species populations and their drought tolerance (*23*) and biomass (fuel) continuity (*24*), thus also affecting fire regime responses to shorter term climate variability]. On interannual and shorter time scales, climate variability affects the flammability of live and dead forest vegetation (*13*–*19*, *25*).

High-quality time series are essential for evaluating wildfire risks, but for various reasons (*26*), previous works have not rigorously documented changes in large-wildfire frequency for

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The following questions address the paper "Probing the Faintest Stars in a Globular Star Cluster" which recently appeared in Science (H. B. Richer, *et al.*, 2006,*SCIENCE*, **313**, 936). Most can be adequately answered with a few lines of text, and perhaps and equation or two, so please be reasonably brief. The questions carry equal weight.

1. Why did the authors chose this particular globular cluster for this investigation? Why not select another globular cluster, another kind of cluster - or simply observe field stars?

The stars in a cluster have a common distance - or very nearly so - and that distance can usually be reasonably well determined by photometric techniques (*e.g.*, main sequence fitting). Moreover, stars within a cluster can be expected to share a common age and (initial) abundance. Mass is essentially the only parameter that really distinguishes one cluster member from another. If one wants to investigate the properties of the most evolved stellar types or the end products of stellar evolution - such as white dwarfs - one needs an old population and the globular clusters include the oldest stellar populations found. (A young galactic cluster might not yet even have acquired a lower main sequence.) Also, there existed suitable earlier and fairly deep HST observations of NGC 6397 which could be used to separate cluster members from field stars *via* their common proper motions. Finally, NGC 6397 is a relatively nearby globular cluster which makes it easier to detect its intrinsically faintest members; the distance and foreground reddening was also quite well determined (Reference 18. As it happens, NGC 6397 is apparently the least reddened of all globular clusters. Messier 4 is the nearest.).

2. What are the nuclear reactions which halt contraction of objects with masses just above the 0.8 solar mass"brown dwarf limit" as they approach the main sequence? Why are these reactions able to (sometimes) halt the contraction? (Hint: Why is the object contracting in the first place?)

Note that there are references to the "hydrogen burning limit" here and elsewhere in the paper. I am looking for a bit more than just that - such as some sort of reference to or description of the proton-proton reaction set and perhaps some mention of the temperature requirements for the onset of this process. A mention of previous deuterium burning - which will occur even for the brown dwarfs - would be a plus. Contraction, and the attendant compressional heating, is halted if and when the thermonuclear energy production rate equals the luminous output of the star and the release of gravitational potential energy attendant upon contraction is no longer needed to provide that energy.

3. Why is the mass range "from about 1 through 7 solar masses" the only part of the stellar mass spectrum considered as progenitors of the white dwarfs in NGC 6397?

The lifetimes of stars much below about a solar mass (about 11 Gyr) exceed the likely cluster age and/or present age of the universe (13.7 Gyr). Stars much above about 7 or 8 solar masses generally end their brief (0.1 Gyr) lives as supernovae and don't leave white dwarfs as remnants. They are long gone, in any case.

4. What, exactly, is the quantity F814W? What is (F606W-F814W)? What is the range of relative brightness of the stars shown in Figure 2?

Some "magnitude" basics. F814W is the astronomical apparent magnitude measured in the relevant wavelength band near 814nm: $m = -2.5\log(\mathrm{Flux}) + \mathrm{const}$. Bigger is fainter, and the constant is set by reference to system standards- and by the choice of units for the observed flux. The second quantity is a color index, a difference in magnitudes corresponding to a ratio in fluxes - again with a system zero point. (Customarily, color indices are defined so as to be zero for a typical AOV star, and arranged so that more positive values correspond to redder sources.) About 20 magnitudes in F814W corresponds to a flux range of about 100 million.

5. The extreme narrowness of the main sequence in the F814W direction - which becomes particularly apparent in the vicinity of (F606W-F814W) ~ 2 - strikes me as a rather "remarkable feature" of Figure 2B; the width is less than 0.2 in F814W. Why do I find this surprising? What does it suggest? (Hint: I would have found an intrinsic dispersion much bigger than 0.75 magnitude puzzling as well.)

Maybe I just don't know any better, but it seems that a reasonable incidence of binaries, comparable to the incidence of field binaries, should provide greater dispersion - albeit less than the 0.75 magnitudes expected of equal-mass pairs. Does the environment of a globular cluster discourage the formation of binary systems - or the disruption of such systems? I can see why it might. Are stars in globular clusters, particularly low mass stars, binary averse?

6. The authors note that these observations, together with theoretical models for white dwarfs, can be used to determine the age of a cluster. How might you accomplish this without those models, using only the data given in this paper?

The "traditional" way of ascertaining a cluster's age is to determine the location of the turnoff point on the upper main sequence. This turn off point can be seen near F814W = 15.7 in Figure 2B, the brighter stars being those which have already left the main sequence to begin their brief lives as giants. The corresponding absolute magnitude is +3.3. The main sequence lifetime of a cluster star of that absolute magnitude should be equal to the cluster age. (It corresponds to a early G-type member of Population II with a lifetime of 11 Gyr or so.) Using a turnoff age is probably more useful for testing white dwarf models than the other way around.

7. Using the information given in the paper estimate the proper motion and transverse velocity of NGC 6397. Is the value you get for the latter reasonable?

This is actually sort of tricky: Since we are looking more-or-less toward the galactic center (l = 338°, b = -12°), and the Galaxy's rotation curve interior to the Sun is roughly linear, the average proper motion of the disk field stars in this field should be close to zero - as would be expected for a rigidly rotating inner disc population. (Note the absence in Figure 3 of a significant F814W *versus* Δr trend in the data for field stars.) The given data indicate that NGC 6397 has moved with respect to the field stars by about 2.5 pixels (0.125") in 10 years. That's a relative proper motion of μ = 0.0125" per year. The distance is "about 8500 light-years" or d = 2,600 pc, so the transverse velocity is about v = 154 km/s (v = 4.74 μd in these units). This is not an unreasonable value for a Population II object. (The proper motion for the galactic center, referenced to an external system of galaxies, should be roughly 0.005 "/yr. That for the field stars, similarly referenced, should be about the same.)

8. The authors suggest that a population of faint metal-poor stars is "awaiting discovery in the halo of the galaxy." On what basis do they suggest that there is an undiscovered population? Are you convinced?

The suggestion of an "undiscovered population" follows from their identification of the redder stars between F814W = 24 and 26 as lower main sequence cluster members. Some might think that identification questionable since there are only about a dozen stars shown in this interval. Moreover, they are rather dispersed in the color magnitude diagram, Figure 2B, unlike the extremely tight main sequence relation defined by cluster stars brighter than F814W = 24. The only indication that these fainter stars might belong to the cluster is their clustering in the proper motion diagram Figure 3C - but even that is not terribly pronounced. (The defining circle drawn in that figure makes the clustering seem more pronounced than it really is.) Maybe, theoretical models to the contrary notwithstanding, the main sequence in NGC 6397 ends at F814W = 24, not 26? Maybe all Population II main sequences end there - in which case there is no need for an "undiscovered population." Note that the "undiscovered" halo stars mentioned by the authors would include halo field stars "evaporated" from globular clusters rather than just members of other globular clusters.

9. What is meant by "electron degeneracy"? It is invoked as being responsible for supporting both "failed" brown dwarfs and the white dwarf end products of stellar evolution.

Again, a mere rephrasing of "the quantum mechanical repulsion between electrons in dense media" given in the paper will not be considered much of an answer. (I'm not sure I like that description anyway.) I expected mention of electrons as fermions and of the Exclusion Principle, at least. The degenerate state is one in which all the lower-lying energy levels are filled and only high mometum/energy states are available for added electrons. And it is only electron degeneracy that is relevant here; the equations of state for the nucleons will reamin nearly that of the ideal gas. . Maybe a comment on the temperature insensitivity of degenerate equations of state. Maybe even a degenerate equation of state, like $P = K\rho^{\gamma}$ with $\gamma = 5/3$ or $4/3$.