Summer 9-6-2005

Galactic Open Clusters

Ted von Hippel
University of Texas, vonhippt@erau.edu

Resolved Stellar Populations
ASP Conference Series, Vol. TBA, 2005
D. Valls–Gabaud & M. Chavez (eds)

Galactic Open Clusters

Ted von Hippel

University of Texas at Austin

Abstract. The study of open clusters has a classic feel to it since the subject predates anyone alive today. Despite the age of this topic, I show via an ADS search that its relevance and importance in astronomy has grown faster in the last few decades than astronomy in general. This is surely due to both technical reasons and the interconnection of the field of stellar evolution to many branches of astronomy. In this review, I outline what we know today about open clusters and what they have taught us about a range of topics from stellar evolution to Galactic structure to stellar disk dissipation timescales. I argue that the most important astrophysics we have learned from open clusters is stellar evolution and that its most important product has been reasonably precise stellar ages. I discuss where open cluster research is likely to go in the next few years, as well as in the era of 20m telescopes, SIM, and GAIA. Age will continue to be of wide relevance in astronomy, from cosmology to planet formation timescales, and with distance errors soon no longer a problem, improved ages will be critically important to many of the most fascinating astrophysical questions.

1. Minimal History of Galactic Open Cluster Research

Rather than linearly review what has been learned about open clusters to date or update the excellent review of Friel (1995), I will use a 44 year old paper by Sandage (1961) as a departure point to cast the problems and opportunities presented by open clusters in perspective. From that brief introduction, I will take a look at 1) the general properties of Galactic open clusters, 2) the most important science to come from open cluster research, and 3) the diverse range of other science derived from open cluster research. All of these topics will be highlighted with work from only the last 1.5 years, since these research fields are so active. I conclude with a brief discussion of the opportunities and challenges of the next ten years.

In 1961, Sandage wrote a short paper entitled "The ages of the Open Cluster NGC 188 and the Globular Clusters M3, M5, and M13 compared with the Hubble Time." Based on his observations and models by Hoyle (1959), Sandage reported that "the ages of the clusters are computed to be 16 x 10^9 years for NGC 188, ...". From these age determinations, and an assumption "if H=75 km/sec/10^6pc", then "available data are therefore inconsistent. Changes in (1) the stellar evolution time scale, (2) the value of the Hubble constant, (3) the observational redshift-magnitude data, or (4) cosmological theory seem to be required at this point." In fact, item 1 changed by a factor of two and item 4 has become considerably more complicated than the $\Omega_{matter} = 1$ Universe many imagined in 1961. For at least 40 years, observations of open clusters and their theoretical interpretation has been deeply coupled to our understanding of stellar evolution, the age of the Universe, and cosmology. I will argue below that the comparison of open clusters to stellar evolution models and the derivation of stellar ages have been the most important science to come of open cluster studies. These studies alone are only part of the vast literature about or relying on open clusters. A statistical look at the literature will help put open cluster research into perspective.

Figure 1 approximates the growth in the research on open and globular clusters over the last 45 years by reporting the number of papers listed by ADS with the phrase "open cluster" or "globular cluster" in the abstract. Such papers are either studies of these star clusters, or are dependent on such studies. The line in the figure is the growth rate in the astrophysics literature, as determined by Abt (1998), normalized to the number of open cluster papers in 1960. Open cluster research followed the general growth trend in astrophysics from 1960 through the late 1980's, after which the expansion of open cluster research was more pronounced. Thus, despite being a classical subject in astronomy, open cluster research remains vital and increasingly relevant. I interpret the current growth in open cluster research to be the result of a renewed desire for precision in stellar population studies plus the steady growth in CCD mosaic sizes. In contrast, globular cluster research appears to have expanded rapidly in the mid-1970's, followed the general growth trend, then leveled off during the last ten years.

2. Overview of Galactic Open Cluster Properties

Galactic open clusters have typical distances of one to a few kpc, largely due to observational bias. They are found primarily in the Galactic plane (Fig. 2, see Jean-Claude Mermilliod's excellent website, http://obswww.unige.ch/webda/ for the data that went into this and some of the following plots), since many of these objects are young (Fig. 3). A more sophisticated study of the age distribution of open clusters is given by Salaris, Weiss, & Percival (2004).

Open clusters show no obvious age-metallicity relation (e.g., Janes 1979; Friel 1995), but they do show a metallicity gradient as a function of Galactocentric distance (e.g., Salaris et al. 2004). Careful studies of open clusters, planetary nebulae, and B stars by a number of groups indicate that $\sim$ 8 Gyr ago, the Galactocentric metallicity gradient was ~ -0.1 dex kpc^{-1}, that it has flattened with time, and that it is now of order -0.04 dex kpc^{-1} (Daflon & Cunha 2004). This result shows the timescale of enriching and mixing within the Galactic disk.

The age-metallicity distribution for open and globular clusters (Fig. 4) shows a complete lack of metal-poor young clusters and shows a tantalizing gap between the ages and metallicities of open clusters versus globular clusters. I interpret that gap not as a fundamental statement of star formation efficiency at [Fe/H] = -0.6 to -0.8, but rather as evidence that the Galaxy evolved rapidly through this intermediate metallicity and/or the star clusters formed at this metallicity survived in even lower fractions than halo globular clusters, only 1% of which survive to date, or open clusters, which survive on Gyr timescales in even lower fractions.

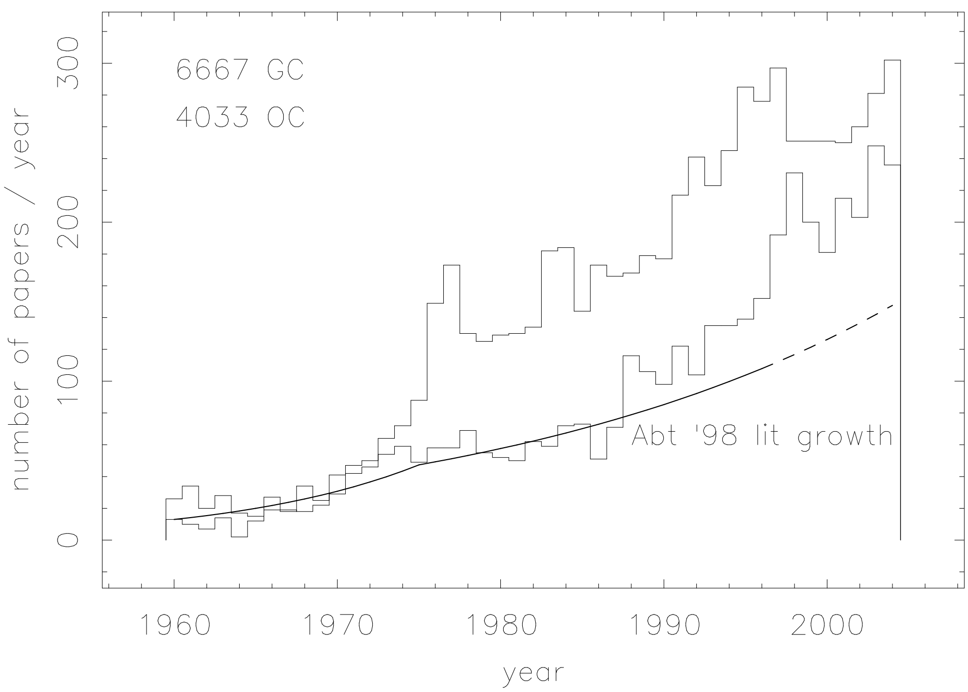

Figure 1. The growth of astronomical literature as a function of year. The overall growth as given by Abt (1998) is indicated by the solid line and extrapolated with the dashed line. The number of papers found by ADS with the phrases "open cluster" and "globular cluster" are given by the lower and upper histogram, respectively, with the number of papers in each category listed at the upper left of the figure.

Interestingly, despite the very low dispersions of open clusters, typically $\leq$ 0.5 km s^{-1} (Mathieu 1985; Zhao & Chen 1994), open clusters lose members steadily, and most eventually dissolve into the Galactic field star population. There is a continuum between open clusters and moving groups and between moving groups and field stars. And the smallest remnants of dissolved open clusters, binary stars, can be thought of as the simplest open clusters. For non-contact binaries, complicated N-body dynamics reduce to well understood 2-body interactions, and these objects have been important for stellar mass studies and distance estimates for about a century.

Since open clusters dissolve readily, the oldest open clusters place only a lower limit on the age of the Galactic disk. Still, that limit is both important and reasonable, with NGC 6791 and Be 17 being $\sim$10 Gyr (Salaris et al. 2004). It is possible, though not convincingly demonstrated, that some of the globular clusters (e.g., 47 Tuc) belong to the thick disk. If this is correct, then these objects place the thick disk at $\sim$12 Gyr (Liu & Chaboyer 2000) old, at or just younger than the age of the Galactic halo and apparently substantially older than the thin disk.

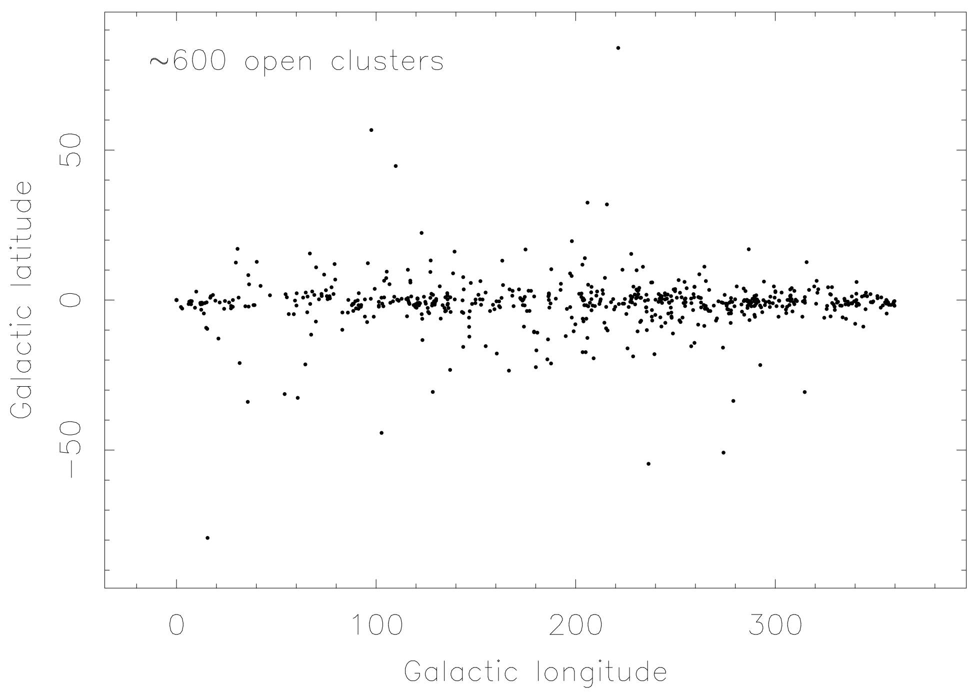

Figure 2. The Galactic longitude and latitude location of all open clusters listed by J.-C. Mermilliod in his web database (obswww.unige.ch/webda/).

Our discussion of the properties of open clusters has unavoidably touched on properties of the Galaxy. While important, in my opinion the most important result from open cluster research is the steady and detailed testing and refining of stellar evolution models.

3. The Most Important Concepts Open Clusters Have Taught Us

We take it as a given that we can model stars and their evolution and that we know the age of any stellar population that we have studied in sufficient detail. But this capability of ours should not be treated as an obvious and trivial extension of physics learned in labs on Earth. Certainly understanding stellar evolution is an extension of physical processes learned in our labs. But understanding stellar evolution is a lot more than that – it is an amazing success, one of the greatest scientific triumphs of the last 50 years. That these distant objects are understandable, even predictable, is a testament to the general applicability of scientific principles. And the derived properties of cluster stars underpins much of Galactic and extragalactic astronomy. In my opinion, the most important parameter to come from the mature field of stellar evolution is the age of stars and stellar systems. Just as the ability to date geological strata rapidly advanced geology, and just as molecular clocks are a key to unraveling evolutionary history of life on Earth, so too the ability to age date stars drives

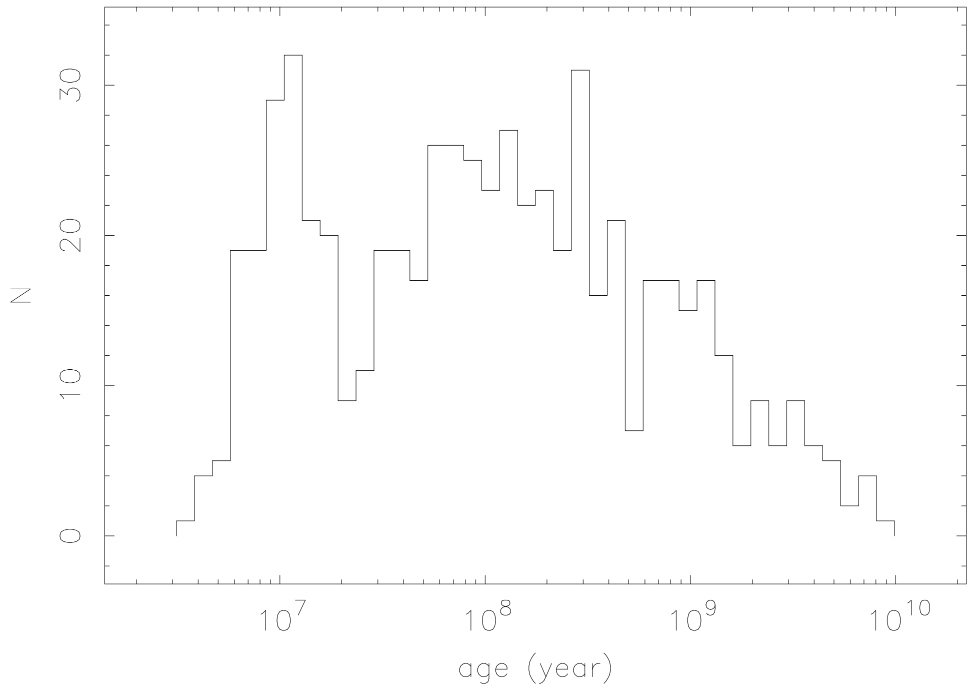

Figure 3. The Galactic age distribution of all open clusters with an estimated age value listed by J.-C. Mermilliod in his web database.

our cosmology. Additionally, the difference between ages often yields important astrophysical timescales. For instance, the difference between the age of the Sun (e.g., Gough 2001) and the planets (e.g., Allègre, Manhès, & Göpel 1995) constrains the timescale for planet formation. Likewise, the difference between the ages of the oldest stars in the Galaxy and the age of the Universe provides the timescale for galaxy formation.

How, exactly, do we determine stellar ages of open clusters? The most common tool, and probably the second most common diagram in astronomy after the spectrum, is the color-magnitude diagram (CMD). The location of stars in the CMD will provide a model-dependent set of correlated constraints on the cluster's age, metallicity, distance, and reddening. Yet, often times cluster CMDs are contaminated by foreground and background Galactic field stars. Such contaminants can be removed by proper motion (e.g., Platais et al. 2003) or radial velocity cuts (e.g., Daniel et al. 1994), or statistically via comparison with an adjacent field or even with Galactic star count models. Even with the addition of outside information to remove contaminating field stars, and despite the maturity of the field of stellar evolution, deriving stellar ages from CMDs is fraught with difficulty. There are uncertainties in theory (see Cassisi, this volume) and uncertainties in the transformation of theory to observations (see VandenBerg, this volume). For example, the detailed studies of the old ($\sim$4 and $\sim$6 Gyr, respectively) open clusters M67 and NGC 188 by VandenBerg &

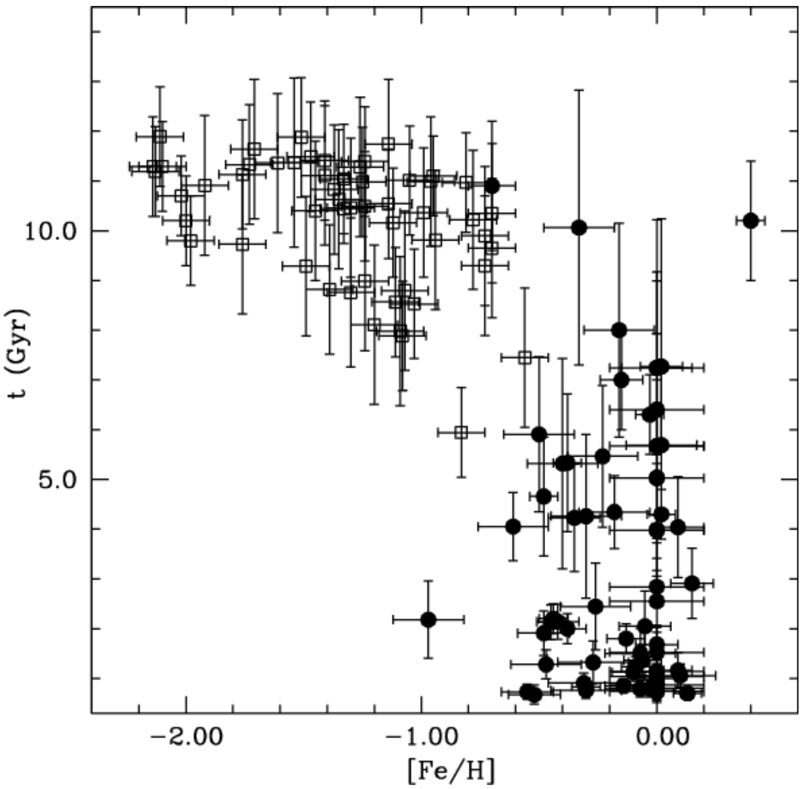

Figure 4. The age vs. metallicity distribution for a large number of open and globular clusters (from Salaris et al. 2004, fig. 10). The open and globular clusters are indicated by the filled circles and open squares, respectively.

Stetson (2004), particularly their figures 3 and 7, show how cluster CMDs can be fit with numerous combinations of cluster age, [Fe/H], stellar helium content, and distance. Additionally, simultaneous fits to CMDs in different colors such as $B - V$ and $V - I$ often do not match the location of the main sequence, turn-off, subgaint branch, or red giant branch in all the CMDs (e.g., for NGC 6791 see Chaboyer, Green, & Liebert 1999 and for NGC 188 see Sarajedini et al. 1999). The theory of stellar evolution is mature and the quality of the data we obtain can be very high, yet important theoretical details still need to be fully understood and the derived parameters, in particular age, are not as precise as we wish them to be. Typical age uncertainties, even in the most carefully studied clusters, are $\pm$ 20%.

Open clusters have not been mined to their full potential, however, and even without improving our telescopes, stellar evolution and stellar atmospheres can be and are being improved and tested on new observations. Model ingredients can be tested on stars in particular states of evolution, especially when there is abundant information on the stellar properties, such as T_{eff} and log(g) from stellar atmospheres, radii from angular measurements or the fortuitous case of eclipsing spectroscopic binaries, and masses from binaries or potentially gravitational redshifts (von Hippel 1996). Another basic model ingredient, the helium content of stars, cannot currently be derived from stellar evolution models, as it is the uncertain mass loss process that drives this quantity, not the amount of helium created by the previous generation of evolving stars. Yet this number too is approachable via observations of open clusters, particularly where multi-color CMDs and independent radii for low mass cluster stars can be obtained.

4. Other Important Concepts Learned from Open Clusters

Open clusters, each containing stars with a range of masses but only a single age, abundance pattern, and distance, have provided tremendous insight into a range of astrophysical problems, from those intimately related to stellar interiors, atmospheres, and evolution, to problems of cosmology, to disk and planet formation.

Figure 5, for instance, shows the lithium abundance vs. $T_{\rm eff}$ for NGC 2547 members and the expectations from 30 Myr and 50 Myr models, appropriate for the cluster age (Jeffries & Oliveira, 2005). The degree of Li depletion as a function of stellar effective temperature and age has been the subject of many studies since the discovery by Boesgaard & Tripicco (1986) of Li depletion in Hyades F stars, and importantly teaches us about stellar surface mixing as well as the photon to baryon density during Big Bang nucleosynthesis (Richard, Michaud, & Richer 2005). Furthermore, placing Li age constraints back into the HR diagram or CMD (see Fig. 6 and also the contribution by E. Martín, this volume), brings the theory of pre-main sequence or main sequence stellar evolution into direct conflict with theories of stellar surface convection and the destruction of Li via nuclear processes. Such a confrontation, here based on the derived ages that best match each theory to the data, could produce the same derived age, or could produce different ages. Coincidences of age are unlikely if either or both theories have substantial problems, especially after studying multiple clusters.

Skipping to another timescale of stars, tidal effects should circularize orbits in non-contact, but closely orbiting, binaries. The distance at which stellar orbits have become circularized should therefore increase as a function of time, and this has been carefully studied both to understand stellar structure and to create a new stellar chronometer that might be useful for field star studies (e.g., Mathieu, Meibom, & Dolan; Meibom & Mathieu 2005). Tidal circularization is a particular form of angular momentum evolution, and other forms, for instance braking in stellar rotation (e.g., Queloz et al. 1998; Melo, Pasquini, & De Medeiros 2001) and star-disk coupling (Carpenter et al. 2005) can also be productively studied in open clusters.

Another important topic of stellar evolution, and one also coupled to stellar ages, is the initial-final mass relation. This is the relationship, often assumed to be monotonic and constant from one cluster to another, between the zero-age main sequence mass of a star, and the mass of its white dwarf (WD) descendant. This relationship is the empirical outcome of the poorly understood process of mass loss during late stages of stellar evolution. It may turn out that mass loss is dependent on stellar rotation, binarity, metallicity, or magnetic fields, and so perhaps no single initial-final mass relation is valid. On the other hand, wild

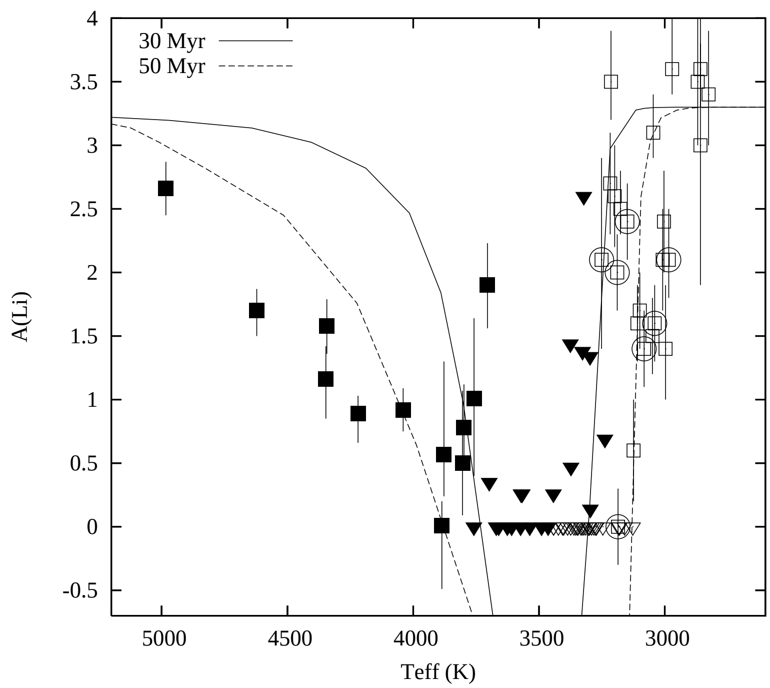

Figure 5. Lithium abundances vs. $T_{\rm eff}$ for NGC 2547 members showing Li depletion as a function of $T_{\rm eff}$ compared to expectations for 30 Myr and 50 Myr models (from Jeffries & Oliveira 2005, fig. 4).

differences in this relationship from cluster to cluster have not been found to date. The upper mass limit for the initial-final mass relation, i.e., the highest mass star that will evolve into a WD, is also an important, and as yet imprecisely constrained number, most likely between 7 and 9 $M_\odot$. This number, in turn, is an important constraint for the theory of stellar evolution and an ingredient in stellar population chemical evolution models. The initial-final mass relation also depends on models of main sequence stellar evolution to determine cluster ages and thereby masses of progenitors, and it furthermore is required to use field WDs as chronometers, as their cooling times need to be added to their progenitor lifetimes in order to derive their ages. For excellent recent studies of the initial-final mass ratio see Williams, Bolte, & Koester (2004) and Kalirai et al. (2005).

A relatively new topic for open cluster research is the connection of open cluster ages to stellar IR excesses. Since we cannot reliable date most single field stars, young clusters with known ages provide the only way to study the evolution of disks. Figure 7, from Mamajek et al. (2004), displays the N-band excess, a proxy for disk mass, for a variety of young clusters. Disk dissipation takes on the order of 10^7 years, which is an important constraint for theories of planet formation. This topic will be of increasing importance as star, disk, and

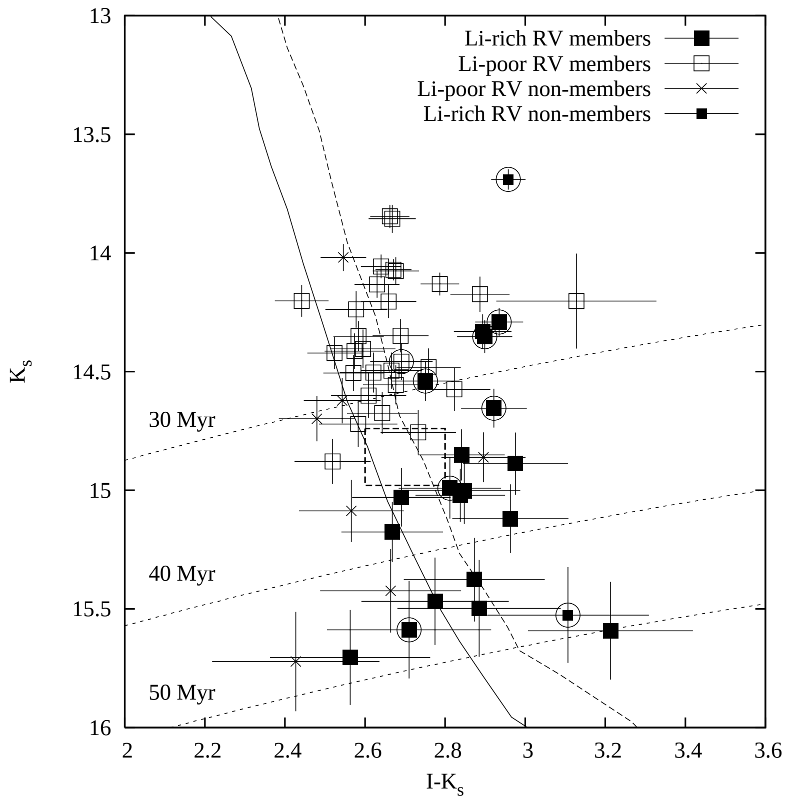

Figure 6. K vs. $I - K$ CMD for NGC 2547 showing standard pre-main sequence isochrones compared with stellar photometry, as well as the time-dependent Li depletion boundary (from Jeffries & Oliveira 2005, fig. 7).

planet formation models and data advance with missions such as Kepler, TPF, and Darwin.

A classic use of open clusters is to calibrate the distance ladder. Every open cluster is amenable to main sequence fitting to derive distance, especially once the cluster metallicity is determined. This is most useful if the reddening is low or independently measured, and there are many such open clusters. In addition, some open clusters contain Cepheids (e.g., Hoyle, Shanks, & Tanvir 2003), others contain eclipsing binaries (e.g., Southworth, Maxted, & Smalley 2005), and a few open clusters are rich enough to calibrate the red clump magnitude (e.g., Grocholski & Sarajedini 2002).

No discussion of open clusters would be complete without mentioning the Initial Mass Function (IMF), yet I will only discuss it briefly, in part because numerous reviews have been dedicated to the subject (Miller & Scalo 1979; Scalo 1986; Mould 1996; Chabrier 2003), and even entire conferences (The Stellar Initial Mass Function: 38th Herstmonceux Conference in 1998), and because the IMF and its derivation are discussed by others at this conference (see contributions by P. Kroupa and J. Maíz Apellániz). Let me merely point out that the observed mass distribution of stars in open clusters results from a combination

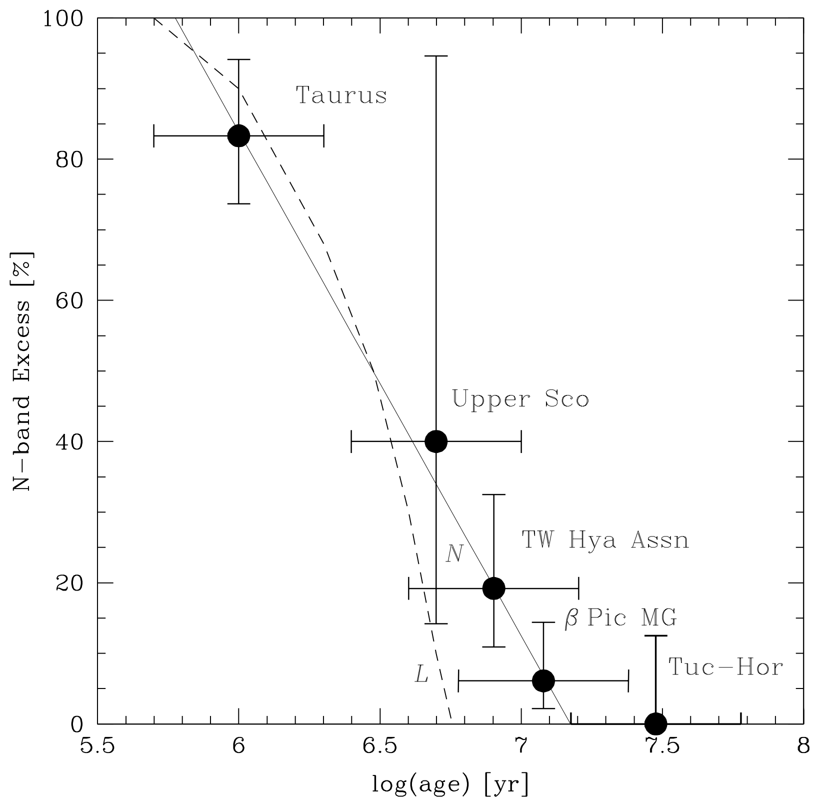

Figure 7. N-band excess, which is a proxy for disks, for young clusters as a function of cluster age (from Mamajek et al. 2004, fig. 3).

of the IMF, stellar evolution, and the cluster's dynamical evolution, and these complexities have, to date, made it difficult to discern whether there is a universal IMF, or whether it varies meaningfully from cluster to cluster. My feeling is that the quality of the data are now good enough to start to discern significant differences from cluster to cluster. Whether these differences will be meaningful in the context of Galactic chemical evolution remains to be seen, and the evidence does not support the range of IMFs often used in extragalactic studies to reconcile necessarily sparse observations with stellar population theory. One of the most impressive aspects of the IMF is that in some clusters, e.g., Lambda Orionis (Barrado y Navascués et al. 2004), observations have now shown that the mass function is smooth until well below the hydrogen burning limit. In this cluster, objects are observed down to $\sim 0.3 M_{\odot}$. Even though this particular mass value is highly uncertain due to difficulties in modeling these stars, a smooth IMF into the brown dwarf regime is a fundamental statement about the star formation process and the limitations of simple Jeans mass explanations for star formation. Clearly more complicated physics are involved in star formation than simply gravity and thermal energy. Turbulence, fragmentation, and interaction most likely play roles in some complicated and probably subtle manner. Additionally, the fact that we can now readily observe brown dwarfs in open clusters provides important opportunities to calibrate their mass-luminosity relationship and to study their atmospheres, formation, and evolution.

5. Where to Next?

5.1. Technology

The current generation of 8-10m telescopes are just now being applied to open cluster problems. Their multiplexing spectrographs are excellent machines to follow-up on wide-field studies at smaller telescopes. Examples of this work are white dwarf spectroscopy to $V \approx 23$ (Kalirai et al. 2005) using both Keck and Gemini. In just over a decade, we should have 20m class telescopes available, and these will make it substantially easier to study brown dwarfs and disks in nearby open clusters. On about the same timescale, NASA's Space Interferometry Mission, will derive exquisite parallax distances (~ 5 microarcseconds, Chaboyer et al. 2005) to important globular clusters. The GAIA mission, a cornerstone mission for ESA, will obtain similar quality astrometry for $\sim 10^9$ stars, including all stars brighter than $V \approx 20$ (de Zeeuw 2005). Distance, which is often the single greatest source of uncertainty in open cluster research, will become a precision parameter. Stellar evolution theory will no longer be able to hide many of its more subtle inadequacies. To take full advantage of these exquisite ages we need to push abundance errors down from their current level of 0.1-0.2 dex, to ≤ 0.05 dex. This should be possible with careful work and high quality spectroscopy.

5.2. Further Refine Theory

Improved distances and metallicities will drive refinements in theory. Yet even before SIM and GAIA, we can hope for improvements as there are a number of approaches that have not been fully exploited. The detailed shape of isochrones and their fits to cluster CMDs as well as stellar number counts along the isochrones for open clusters covering a range of ages have already been used to tune stellar evolution parameters such as overshoot (e.g., Demarque et al. 2004). This process can be continued for other clusters and with better data, and other stellar evolution parameters can be improved upon via this technique. The overly simplistic mixing length theory is one example that needs refinement, and this is being pursued (Canuto, Goldman, & Mazzitelli 1996; Kupka & Montgomery 2002). The spectroscopy of highly evolved stars also yields clues to dredge-up and other mixing processes, and the study of pulsating stars holds out hope for refining stellar structure in a manner entirely independent of matching the external properties of stars to interior models plus atmosphere models.

Another technique where observations can test and help guide theory, is the simultaneous age dating of cluster WDs and cluster main sequence turn-off (MSTO) stars. Since a single cluster has one age, both the WD cooling ages and the main sequence stellar evolution ages should agree. The WD observations have been demanding in the past, but with the current abundance of 8-10m telescopes as well as HST with the ACS instrument, more of the very faint (=old) WDs in open clusters have been observed. Open clusters with a range of ages and abundances are now being studied via this technique (see von

Hippel 2005, and references therein) and one globular cluster, M4, has been observed to sufficient depth for a WD age (Hansen 2004). In this volume, Jeffery et al. demonstrate a Bayesian modeling technique that holds promise for deriving cluster WD ages even in cases where the faintest WDs are too faint to be observed. Their technique, while still being developed, should allow us to add more distant star clusters to our studies and widen the applicability of the WD technique. Figure 8 presents the current status of cluster age studies where both the WD cooling technique and the traditional main sequence evolutionary age technique have been applied. The good news is that stellar evolutionary timescales appear firm to 2 Gyr and probably 4 Gyr. (I emphasize the match to 2 Gyr and the uncertainty at 4 Gyr since the 4 Gyr cluster, M67, anchors the upper age end by itself and since the WD age was derived after a statistical background subtraction (Richer et al. 1998)). Many more clusters can be added to this comparison, and this should and will be done.

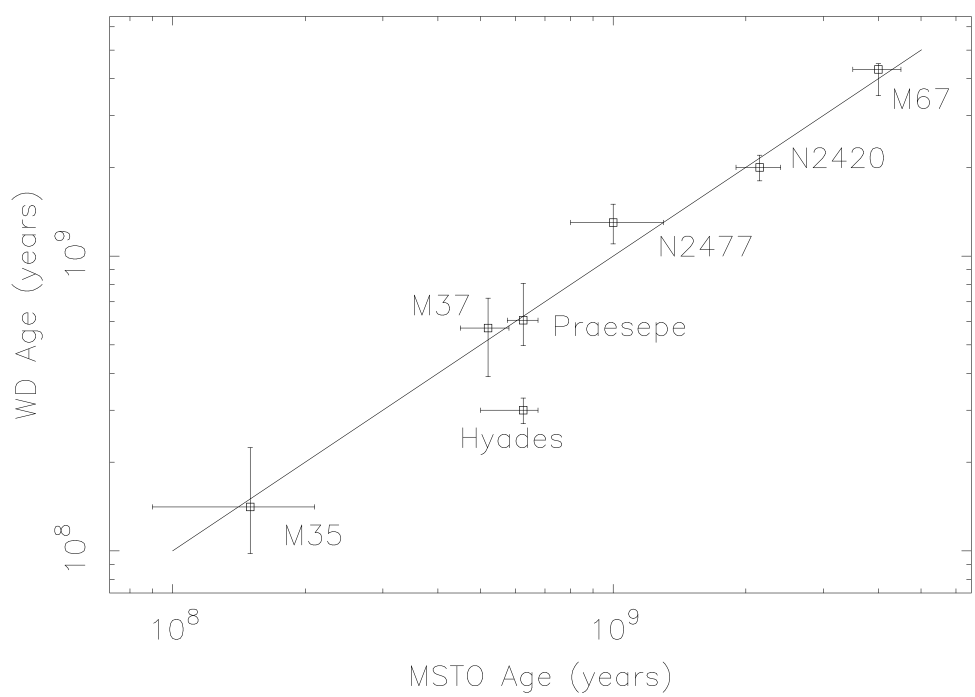

Figure 8. Main sequence turn-off age vs. white dwarf age for seven clusters (from von Hippel 2005, fig. 1).

It is important to test the most important parameter of our stellar evolutionary models whenever possible. At this conference, during Eduardo Martín's talk, I realized there is hope for an WD age vs. MSTO age vs. Li age test for at least a few young clusters. And there may be other multiple age tests, at least at the level of a consistency check, for instance with stellar circularization or disk dissipation. The goal in these tests is to bring into potential conflict the most important derived quantities of the theory, and thereby both test the theory and provide an empirical estimate of the accuracy of the predicted quantities.

5.3. Highest Impact Science

I believe that stellar ages will remain the highest impact science to come from open cluster research for some time. Refinements in theory and improvements in distances, metallicities, etc. can drive age precisions from the present best case of $\sim 20\%$ to perhaps 5%. Stellar ages, in turn, will refine our understanding of the formation sequence and structure formation process in the Galaxy. A refined stellar evolution theory coupled with exquisite GAIA distances to field stars will also make it possible to derive ages for many of the slightly to moderately evolved field stars. Improved age precision will in turn be necessary for answering questions in new fields, such as stellar disk dissipation and planet formation timescales. It is also possible that our colleagues will soon discover planets in open clusters, via the transit, radial velocity, or direct imaging techniques. The properties of planets in systems with known ages will be substantially more useful for understanding planet formation and evolution than similar planets found around field stars of uncertain age.

6. Conclusion

The study of open clusters has a classic feel to it since the subject predates any of us. Despite the age of this topic, its relevance and importance in astronomy has grown faster in the last few decades than our field in general. This is due to both technical reasons and the interconnection of the field of stellar evolution to many branches of astrophysics. Large field of view imagers on 4m class telescopes, multi-plexing spectroscopy on 8-10m telescopes, and HST are all contributing to the rapid growth in open cluster research. The topics open clusters can address, ranging from subtleties of stellar evolution to the distance ladder to disk dissipation and planet formation timescales, indicates that these star clusters that we have been fortunate to live among will continue to be important research arenas for decades to come.

Acknowledgments. I would like to thank David Valls-Gabaud and the SOC for inviting me to present this review, and the LOC for their organizational, professional work. This material is based upon research supported by the National Aeronautics and Space Administration under Grant No. NAG5-13070 issued through the Office of Space Science, and by the National Science Foundation through Grant AST-0307315.

References

Abt, H. A. 1998, PASP, 110, 210
Allègre, C. J., Manhès, G., & Göpel, C. 1995, GeCoA, 59, 1445
Barrado y Navascués D., Stauffer, J. R., Bouvier, J., Jayawardhana, R., Cuillandre, J.-C. 2004, ApJ, 610, 1064
Boesgaard, A. M., & Tripicco, M. J. 1986, ApJ, 302, L49
Canuto, V. M., Goldman, I., & Mazzitelli, I. 1996, ApJ, 473, 550

Carpenter, J. M., Wolf, S., Schreyer, K., Launhardt, R., & Henning, T. 2005, AJ, 129, 1049
Chaboyer, B., et al. 2005, AAS, 206, 1409
Chaboyer, B., Green, E. M., & Liebert, J. 1999, AJ, 117, 1360
Chabrier, G. 2003, PASP, 115, 763
Daflon, S., & Cunha, K. 2004, ApJ, 617, 1115
Daniel, S. A., Latham, D. W., Mathieu, R. D., & Twarog, B. A. 1994, PASP, 106, 281
Demarque, P., Woo, J.-H., Kim, Y.-C., & Yi, S. K. 2004, ApJS, 155, 667
de Zeeuw, P. T. 2005, Proc. of the Gaia Symp., ESA SP-576, eds. C. Turon, K. S. O'Flaherty, & M. A. C. Perryman, 729
Friel, E. D. 1995, ARA&A, 33, 381
Friel, E. D., & Janes, K. A. 1993, A&A, 267, 75
Hansen, B. M. S., et al. 2004, ApJS, 155, 551
Gilmore, G., & Howell, D., eds., 1998, The Stellar Initial Mass Function: 38th Herstmonceux Conference, ASP Conf. Ser. 142
Gough, D. O. 2001, in ASP Conf. Ser. 245, Astrophysical Ages and Time Scales, ed. T. von Hippel, C. Simpson, & N. Manset (San Francisco: ASP), 31
Grocholski, A. J., & Sarajedini, A. 2002, AJ, 123, 1603
Hoyle, F. 1959, MNRAS, 119, 124
Hoyle, F., Shanks, T., & Tanvir, N. R. 2003, MNRAS, 345, 269
Janes, K. A. 1979, ApJS, 39, 135
Jeffries, R. D., & Oliveira, J. M. 2005, MNRAS, 358, 13
Kalirai, J. S., Richer, H. B., Reitzel, D., Hansen, B. M. S., Rich, R. M., Fahlman, G. G., Gibson, B. K., & von Hippel, T. 2005, ApJ, 618, L123
Kupka, F., & Montgomery, M. H. 2002, MNRAS, 330, L6
Liu, W. M., & Chaboyer, B. 2000, ApJ, 544, 818
Mamajek, E. E., Meyer, M. R., Hinz, P. M., Hoffmann, W. F., Cohen, M., & Hora, J. L. 2004, ApJ, 612, 496
Mathieu, R. D. 1985, in Dynamics of Star Clusters, eds. J. Goodman & P. Hut (Dordrecht: Reidel), 427
Mathieu, R. D., Meibom, S., & Dolan, C. J. 2004, ApJ, 602, L121
Meibom, S., & Mathieu, R. D. 2005, ApJ, 620, 970
Melo, C. H. F., Pasquini, L., & De Medeiros, J. R. 2001, A&A, 375, 851
Miller, G. E., & Scalo, J. M. 1979, ApJS, 41, 513
Mould, J. 1996, PASP, 108, 35
Platais, I., Kozhurina-Platais, V., Mathieu, R. D., Girard, T. M., & van Altena, W. F. 2003, AJ, 126, 2922
Queloz, D., Allain, S., Mermilliod, J.-C., Bouvier, J., & Mayor, M. 1998, A&A, 335, 183
Richard, O., Michaud, G., & Richer, J. 2005, ApJ, 619, 538
Richer, H. B., Fahlman, G. G., Rosvick, J., & Ibata, R. 1998, ApJ, 504, L91
Salaris, M., Weiss, A., & Percival, S. M. 2004, A&A, 414, 163
Sandage, A. R. 1961, AJ, 66, 53
Sarajedini, A., von Hippel, T., Kozhurina-Platais, V., & Demarque, P. 1999, AJ, 118, 2894
Scalo, J. M. 1986, FCPh, 11, 1
Southworth, J., Maxted, P. F. L., & Smalley, B. 2005, A&A, 429, 645
VandenBerg, D. A., & Stetson, P. B. 2004, PASP, 116, 997
von Hippel, T. 1996, ApJ, 458, L37
von Hippel, T. 2005, ApJ, 622, 565
von Hippel, T., & Gilmore, G. 2000, AJ, 120, 1384
Williams, K. A., Bolte, M., & Koester, D. 2004, ApJ, 615, L49
Zhao, J. L., & Chen, L. 1994, A&A, 287, 68