Open cluster age research

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| Galactic Open Clusters = review article  Ted Von Hippel  <https://arxiv.org/pdf/astro-ph/0509152.pdf>  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  A more sophisticated study of the age distribution of open clusters is given by Salaris, Weiss, & Percival (2004). |
| **The age of the oldest Open Clusters**  <https://arxiv.org/pdf/astro-ph/0310363.pdf>  The age of the oldest open clusters (NGC 6791 and Be 17) is of the order of 10 Gyr. We determine a delay by 2.0 ±1.5 Gyr between the start of the halo and thin disk formation, whereas thin and thick disk started to form approximately at the same time.  The cumulative age distribution does not show any trend with galactocentric distance, but the clusters with larger height to the Galactic plane have an excess of objects between 2–4 and 6 Gyr with respect to their counterpart closer to the plane of the Galaxy.  The theory of the formation of galaxies is without any doubt one of the outstanding problems of astrophysics.  we do not have yet a complete and definitive picture of how galaxies form  A way to shed some light on this problem is to study the timescale for the formation of the different Galactic populations, e.g., halo, thick disk, thin disk and bulge, by means of stellar age dating. The most reliable stellar ages are obtained for the star clusters belonging to the various populations, i.e., the globular clusters (GCs) in the halo, thick disk and bulge, and the open clusters (OCs) in the thin disk. The advantage of dating star clusters over individual stars – whose age determination relies entirely on the knowledge of individual metallicities, effective temperatures and gravities (or absolute magnitudes), which have to be fitted by the appropriate theoretical model – stems from the fact that star clusters are made of coeval objects, largely with the same initial chemical composition and located at the same distance, so that it is possible to use morphological parameters deduced from theoretical isochrones in order to derive their age. In this way one can bypass the thorny problem of determining a reliable empirical and theoretical temperature scale, and of acquiring high resolution spectroscopy for large samples of stars. |
| **Nearly coeval intermediate-age Milky Way star clusters at very different dynamics evolutionary stages**  The study of Galactic open clusters has long helped improve our  understanding of the Milky Way disc formation and evolution. For  instance, from their positions, ages and metallicities, the radial  metallicity gradient as well as that perpendicular to the Galactic  plane have been derived, which in turn have been used to constrain  Milky Way formation theoretical models (Magrini et al. 2009;  Sahijpal & Kaur 2018)  With the aim of contributing to a comprehensive knowledge of the open cluster system |
| **Star Clusters in Evolving Galaxies**  <https://arxiv.org/pdf/1801.04278.pdf>  Star clusters form in dense gas clouds, of which assembly is triggered, set and regulated by galactic-scale hydrodynamics, itself influenced by the inter-galactic and cosmological environment.  Once formed, stars in clusters alter the morphology, energy and chemistry of their nurseries through stellar feedback  In the end, the formation and evolution of star clusters is the results of a complex interplay of dynamical and hydrodynamical (and probably magnetic) processes from intergalactic scales (∼ 10 Mpc, ∼ 10 Gyr), down to stellar scales (∼ 10−3 pc, ∼ 1 day), all this happening for most of the life of the Universe.  This wide diversity of scales and physical processes makes it difficult to propose holistic theories. Yet, significant progresses on individual concepts have been made in the last few decades, and coupling several aspects together is now routinely achieved in theories, simulations and interpretation of observations.  star clusters differ from stellar associations and moving groups by being gravitationally bound (see Zuckerman and Song, 2004, and references therein). Gieles and Portegies Zwart (2011) further proposed that objects with crossing times longer than the age of their stars would likely be unbound and should thus be classified as associations.  Most of the globular and nuclear clusters do indeed yield relaxation times shorter than a Hubble time (which qualifies them as collisional systems)  The relaxation time quantifies how long a stellar system takes to erase signs of a perturbation, through star-star encounters and exchanges of energy toward equipartition (see Section 10 for more details). For old systems (i.e. with an average stellar mass of 0.5 M) in the mass range of 105 – 8 M, a relaxation time shorter than a Hubble time corresponds to a half-light radii of 1 – 6 pc.  For long, globular clusters have been thought to consist of stars with a common origin, i.e. that formed at the same place, same time and thus from the same material (e.g. Ashman and Zepf, 1998).  The situation depicted above leads to the absence of a clear, unambiguous and practical definition of star clusters (and thus also of galaxies, see Forbes and Kroupa 2011).  Even defining star cluster members as being gravitationally bound can be a dangerous shortcut. Stars with sufficient energy to potentially escape their cluster can be trapped for a significant amount of time and appear as cluster members (see Section 13.2)  A lot of progresses have been made over the last years, thanks to increasingly powerful resources like the Hershel Space Telescope, ALMA, MUSE, NOEMA, and supercomputers capable of handling the large amount of data on these interconnected subjects and running always improving models.  Observational surveys in the Milky Way show that the dense, cold gas (e.g. traced by CO) is organised in clumps with typical masses and radii of ∼ 106 M and ∼ 10 − 30 pc (Solomon et al., 1987; Dame et al., 2001). These giant molecular clouds (GMCs), embedded in envelops of atomic gas (with comparable mass, see e.g. Blitz et al. 1990), host dense enough gas to potentially form star clusters (& 100 – 1000 cm−3 ). Measuring observationally the inner properties of these clouds (and a fortiori the sites of individual star formation) is limited to the Milky Way and nearby galaxies (LMC, SMC, M 31, M 33, etc., see e.g. Rosolowsky 2007; Rosolowsky et al. 2007, Miville-Deschenes et al. 2017 ˆ with estimates of cloud properties over the entire Milky Way disc, and Hughes et al. 2013 in the more distant M 51), all representing relative quiescent environments, with low star formation rates (∼ 1 M yr−1 ). Comparable studies in more active galaxies, including mergers and starbursts like M 82, will only become possible in a few years  All stars seem to form in clusters (Lada and Lada, 2003), and even though all these clusters are not necessarily bound and could be dynamically destroyed within a few Myr (Bressert et al., 2010), the important point here is that star nurseries host the formation of more than one star, in turbulent molecular clouds (Hennebelle and Falgarone, 2012). It must be noted that no star formation mechanism actually requires the gas to be molecular to form stars. Yet, after the cooling from freefree emission in charged plasma (& 106 K, i.e. important to cool gas in galactic halos), the collisional recombination (i.e. the inverse of the ionization process) and the atomic de-excitation (∼ 104 – 5 K, Baugh 2006), the scarcity of free particles in atomic gas to exchange energy with (and thus radiate energy away and cool down) makes atomic cooling rather inefficient below ∼ 104 K. 1 Molecular gas (and dust) however yields more numerous and lower energy levels that allow efficient cooling below 104 K (e.g. the CO rotational line emission), thus reducing the internal pressure of clouds and allowing self-gravity to increase the density enough to trigger fragmentation and collapse into cores (see e.g. Glover and Clark, 2016). |

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| **Ted von Hippel 2005 (review) Galactic Open Clusters**  Why open clusters are important: connected to stellar evolution  Provides one of the most precise stellar ages.  Open clusters are mostly found in the galactic plane (as expected)  Database of clusters: Jean-Claude Mermilliod’s excellent website, http://obswww.unige.ch/webda/  Age distribution of these clusters: 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).  Since open clusters dissolve readily, the oldest open clusters place only a lower limit on the age of the Galactic disk.  NGC 6791 and Be 17 being ∼10 Gyr (Salaris et al. 2004)  Colour magnitude diagram (CMD) = star clusters’ version of HR diagram  2. A. L. Tadross 2014 The astrophysical behavior of open clusters along the Milky Way Galaxy  A table that includes age of a large number of clusters  A general look at the positions of open clusters in the milky way galaxy, and the spread regarding the distance from the galactic plane, and distance from the galactic centre.  Did some constraints to cluster size and R\_lim (don’t know what this is)  Linear size of open clusters increases with ages |
| “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).  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.  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” – Hippel review      Typical age uncertainties, even in the most carefully  studied clusters, are ± 20%.  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.  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.  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.    “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.”  <https://arxiv.org/pdf/astro-ph/0509152.pdf>  <https://royalsocietypublishing.org/doi/full/10.1098/rsta.2009.0253>  <https://www.sciencedirect.com/science/article/pii/S2090997714000224> |
| The age of the oldest Open Clusters  M. Salaris  <https://www.aanda.org/articles/aa/abs/2004/04/aah4736/aah4736.html>  <https://arxiv.org/pdf/astro-ph/0310363.pdf>  They determined the ages of old Open Clusters by using main-squence fitting to 10 selected clusters, in order to obtain their distances, and derive their ages from comparison with some isochrones used before for Globular Clusters.  The age of the oldest open clusters (NGC 6791 and Be 17) is of the order of 10 Gyr.  They determined a delay by 2.0 ± 1.5 Gyr between halo and thin disk formation (thin and thick disk form approximately at the same time)  They did not find any significant age–metallicity relationship for the open cluster sample.  “The cumulative age distribution does not show any trend with galactocentric distance, but the clusters with larger height to the Galactic plane have an excess of objects between 2–4 and 6 Gyr with respect to their counterpart closer to the plane of the Galaxy.” |
| Star Cluster Ages in the Gaia Era - J Choi, ‎2018  <https://arxiv.org/pdf/1807.03789.pdf>  Used the recent Gaia Data Release 2 (DR2) along with data from the literature to investigate three well-studied old open clusters—NGC6819, M67, NGC6791  Identified the likely cluster members with HDBSCAN clustering algorithm (Campello et al. 2013)  “HDBSCAN identifies clusters based on the density of points and, importantly, does not force all data points to belong to a detected cluster”  **NGC6819** is a solar-metallicity, intermediate-age (2 Gyr),  richly populated open cluster  Yang et al. 2013 <https://arxiv.org/pdf/1211.0077.pdf> - they say NGC6819 has an age of 2.6 Gyr  “According to the latest compilation of known Galactic open clusters (i.e., Open clusters and Galactic structure, Version 3.2, http://www.astro.iag.usp.br/∼wilton; Dias et al. 2012), now numbering over 2000.  New catalog of optically visible open clusters and candidates  <https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3table.pl?tablehead=name%3Dopenclust&Action=More+Options>  <http://cdsarc.u-strasbg.fr/ftp/cats/B/ocl/v3.3/>  <https://www.aanda.org/articles/aa/pdf/2002/27/aa2476.pdf>  AnthonyTwarog et al. 2014; Lee-Brown et al. 2015).  The rotation rates of all cool stars decrease substantially with time as the stars steadily lose their angular momenta. If properly calibrated, rotation therefore can act as a reliable determinant of their ages based on the method of gyrochronology  To calibrate gyrochronology, the relationship between rotation period and age must be determined for cool stars of different masses, which is best accomplished with rotation period measurements for stars in clusters with well-known ages. Hitherto, such measurements have been possible only in clusters with ages of less than about one billion years and gyrochronology ages for older stars have been inferred from model predictions. Here we report rotation period measurements for 30 cool stars in the 2.5-billion-year-old cluster NGC 6819. The periods reveal a well-defined relationship between rotation period and stellar mass at the cluster age, suggesting that ages with a precision of order 10 per cent can be derived for large numbers of cool Galactic field stars.  “The (unaltered) model of gyrochronology from ref. 11 provides a good fit to the data over nearly the full colour range of the observations. To test the precision of gyrochronology we may thus treat the coeval NGC 6819 stars as individual field stars, and ask what age the model of ref. 11 would provide for each of the 21 best-measured stars, that is, those with (B − V)0 colour index between 0.55 and 0.9 mag (masses between ∼1.1 and ∼0.85 that of the Sun). Every one of these stars returns a gyro age between 2 and 3 Gyr, with a roughly Gaussian distribution centred at 2.49 Gyr (Extended Data Fig. 9). The standard deviation of the 21 ages is 0.25 Gyr (10% of the mean gyro age), implying that ages of this precision can be derived for similarly well-measured field stars, despite the effects of measurement errors, differential rotation and a spread in initial rotation periods.”    A spin-down clock for cool stars from observations of a 2.5-billion-year-old cluster  <https://www-nature-com.ezproxye.bham.ac.uk/articles/nature14118> |
| M67 is a nearby solar-metallicity, intermediate-age (4 Gyr)  open cluster (Taylor 2007; Sarajedini et al. 2009; Önehag  et al. 2014).    <https://watermark.silverchair.com/stw700.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAAlwwggJYBgkqhkiG9w0BBwagggJJMIICRQIBADCCAj4GCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMK3CGWcKw_tEtlWlWAgEQgIICD7zwmnhiCLmq4spzABJeCJL2-OyzFBZ9jOrDI_9kZGHwkmeKl93CNC0AXa8yrQbQCrxrpvLBkWKeAMYTQ31c16vFBx2k7lY2IIxE8xMd7ycc9k9XjOq5O-GWh90Ck_9MdSEjoZOpHouQdxTEr_VI2XHzMliHQib4gbrQp8VFg6z0X9uLLRq-GQ4gwWrbKtTXb_syzNEpkHnJD0CXbLHmOKrmrFT9pa0QK_wNTfZ_-7m6fR1XgpkwaxeTtCAXCP8c-mQuOOkyqHVZXm6EFYRC0WKLUY33ppgg9r9dT3YyR5WLAW8KbYT-i_LU1SbZ_z0oYHsCaJvI06cp1CqT0XxLF_VSuCJAGlPd63occYroMl8zvenGDIOvOpJId5qNqa4uDWU04Oz3-dxM9OpiqMkUjM4--TE_zLu1ojhZLrNegKnouEku_YfRHKNVU5CKFK913dHpvXLXF4Xm2qime_fxod7ygd3tL6TtKwhUsCQek_xRNqd2551Sr3GtyAwp20DNGWlXx8dro7aNKUOJDbWr2ffrV9-ecFkm3dfgzRIlg_B-4I2-xt3zRFJRj2ijpCMbo2SR3Ce9Q1HY_s4txnfVinOhZEthZBZUMzmr23CGq_MY_RRZsqTcEGr5yrb4VbCZONsXYvCH4zjgpzlvpafOHl5tWQdz0MIGil_OpyfXg1hKyqSNs8KOQb5R_Xytni8D> |
| NGC6791 is an exceptionally old (8 Gyr) and metal-rich  ([Fe/H]≈0.3–0.5) open cluster (e.g., Stetson et al. 2003; Gratton et al. 2004; Carney et al. 2005; King et al. 2005; Origlia  et al. 2006; Linden et al. 2017). It is also well-known for  its puzzling double white dwarf cooling sequence, both of  which imply cluster ages that are nominally inconsistent with  the MSTO age (Bedin et al. 2005, 2008a but see also GarcíaBerro et al. 2010). Several explanations have been put forth,  including the presence of a secondary population of massive  helium WDs (Hansen 2005; Kalirai et al. 2007) and WD binaries (Bedin et al. 2008b).  “NGC 6791, which is old, but super-metal-rich with high-resolution  (R = 46,000) Keck/HIRES spectra. We find [Fe/H] = +0.30 ±0.02 from measurements of some  40 unblended, unsaturated lines of both Fe I and Fe II in eight turn-off stars.”  <https://arxiv.org/pdf/1412.8515.pdf>  NGC 6791 is an extreme Galactic star cluster with an old age of ∼8 Gyr (Grundahl et al. 2008)  <https://iopscience.iop.org/article/10.1088/2041-8205/733/1/L1/pdf>  “The cluster age is obtained from comparisons with theoretical isochrones in the mass-radius diagram. Using the isochrones from Victoria-Regina with [Fe/H] = +0.37 we find 7.7 ± 0.5 Gyr, whereas the Yonsei-Yale (Y2) isochrones lead to 8.2 ± 0.5 Gyr, and BaSTI isochrones to 9.0 ± 0.5 Gyr. In a mass-radius diagram, the 7.7 Gyr VRSS and 9.0 Gyr BaSTI isochrones overlap nearly perfectly despite the age-difference.  Conclusions. Using detached eclipsing binaries for determination of cluster ages, the dominant error is due to differences among stellar models and no longer to observational errors in cluster reddening and distance. By observing a suitable number of detached eclipsing binaries in several open clusters it should be possible to calibrate the age-scale and provide firm constraints which stellar models must reproduce.”  <https://www.aanda.org/articles/aa/abs/2008/46/aa10749-08/aa10749-08.html>    <https://iopscience.iop.org/article/10.1086/504829/pdf>  Fig 4+5+6 <https://www-aanda-org.ezproxye.bham.ac.uk/articles/aa/pdf/2012/07/aa19196-12.pdf>  Looked promising (no age but asteroseismic analysis) <https://iopscience.iop.org/article/10.1088/0004-637X/739/1/13/pdf> |
| <https://arxiv.org/pdf/1603.00474.pdf>  <https://arxiv.org/pdf/1211.0077.pdf>  <https://arxiv.org/pdf/1403.7208.pdf>  <https://arxiv.org/pdf/1811.00311.pdf>  <https://arxiv.org/pdf/astro-ph/0505019.pdf> <https://arxiv.org/pdf/1309.0608.pdf>  <https://iopscience-iop-org.ezproxye.bham.ac.uk/article/10.1088/0004-637X/722/1/222> = lots of maths |
| It is understood that the most of the massive clusters in the solar neighbourhood would  dissolve even before reaching the age of 1 Gyr causing the deficiency of old clusters in  the solar neighbourhood.  <https://arxiv.org/pdf/1707.09126.pdf> |
| Review article: <https://royalsocietypublishing.org/doi/full/10.1098/rsta.2009.0253>  Review article with a number of open cluster ages: <https://www.sciencedirect.com/science/article/pii/S2090997714000224#b0210> |
| CENTER DETERMINATION  To estimate the cluster center theoretically, it can be defined as either the center of mass or the location of the deepest part of the gravitational potential. Observationally, the center is often defined as the region of the highest surface brightness or the region containing the largest number of stars (Littlefair et al. 2003). Here, the cluster center is defined as the location of maximum density of probable member stars, after applying the color-magnitude filters. The optimized cluster centers can be obtained by fitting a Gaussian to the profiles of star counts, in equal incremental strips, in right ascensions and declinations.  <https://arxiv.org/pdf/1108.2134.pdf> pretty good paper |
| M67 = NGC2682  <http://simbad.u-strasbg.fr/simbad/sim-id?Ident=M+67&jsessionid=C6D180C16C9A0404FC3260A649C1AF56.main>  <http://www.messier.seds.org/xtra/supp/m_NED.html#m67>  <http://ned.ipac.caltech.edu/cgi-bin/nph-objsearch?objname=M+67&extend=yes&out_csys=Equatorial&out_equinox=J2000.0&obj_sort=RA+or+Longitude&zv_breaker=30000.0&list_limit=5&img_stamp=YES> |
| NGC6819  3 Red giant ages: <https://www.epj-conferences.org/articles/epjconf/pdf/2015/20/epjconf_sphr2014_06001.pdf>  Asteroseismic data but not age: <https://pure.au.dk/ws/files/134478260/NGC_6819_testing_the_asteroseismic_mass_scale_mass_loss_and_evidence.pdf> |