Understanding Stellar Associations and Clusters

with Constrained Theoretical Models

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Internship supervised by C. M. Boily and P. Guillout
at the Observatory of Strasbourg

Wednesday 29th May, 2024

Faculté de physique et ingénierie Université de Strasbourg

Observatoire astronomique de Strasbourg | ObAS

Introduction and Contents

- Study star clusters with theory, simulations and observations
- Internship in pair with Simon Perrier

What is a Star Cluster?

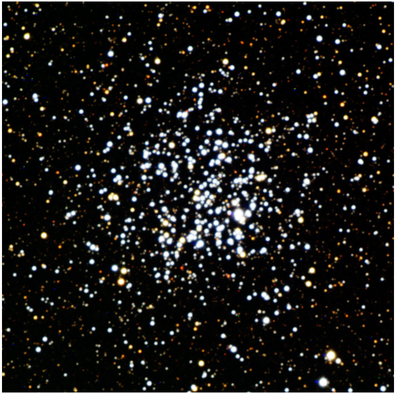

Figure 1: M 11, an open cluster.

Figure 2: M 3, a globular cluster.

Observation of a Star Cluster: Observation Platform

Figure 3: The 2T36 at the Observatory of Strasbourg.

- Two telescopes:
  - → Photometry and imaging
  - → Spectroscopy and guiding
- Schmidt-Cassegrain
- Aperture: 36 cm
- Focal length: 391 cm
- Filter wheel (B, V, R, Ic, Hα, Hβ, OIII)

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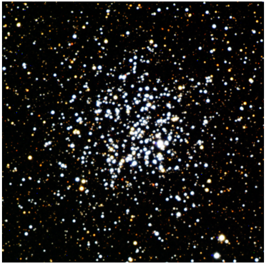
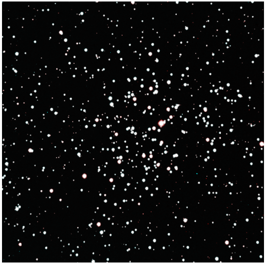
Methods: Clusters in Archives

(a) M 3 (NGC 5272)



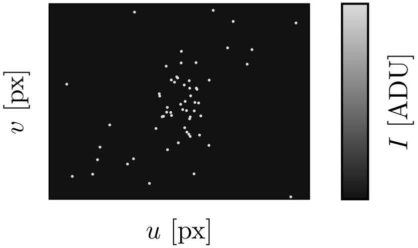
(b) M 11 (NGC 6705)



(c) M 37 (NGC 2099)

Figure 4: The three clusters studied during this internship with three filters: B ($\sim$ 420 nm), V ($\sim$ 530 nm) and R ($\sim$ 600 nm).

Methods: Processing



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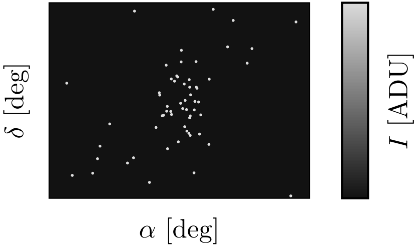

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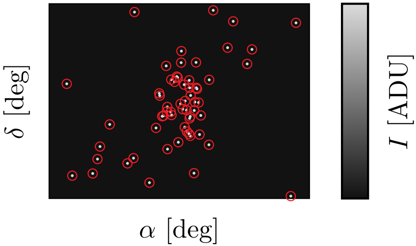

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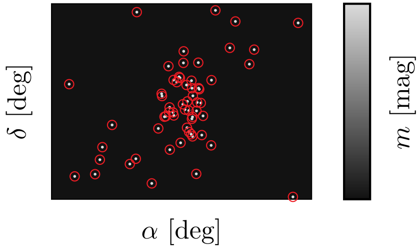

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- Filtering: `Gaia` x-match (Gaia Collaboration et al., 2016, 2023)

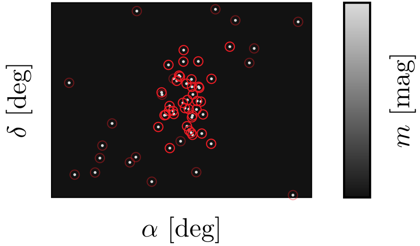

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Figure 6: Color-Magnitude Diagram or Hertzsprung–Russell Diagram.

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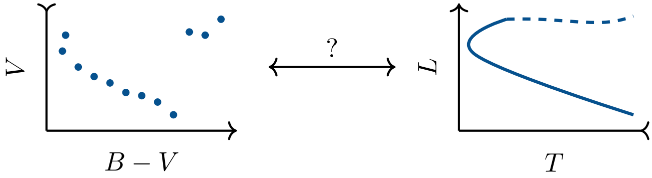

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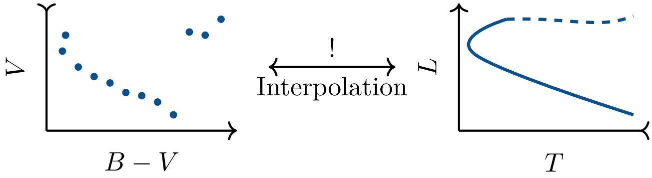
  - → Stellar atmospheric simulations: `ATLAS9` (Castelli &Kurucz, 2003)
  - → Interpolation: `YBC` tables (Chen et al., 2019)



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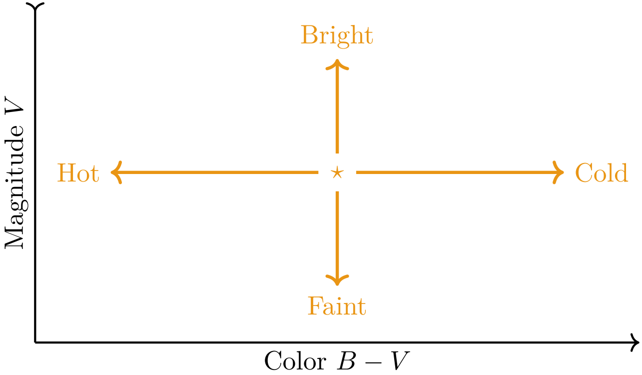
Methods: Hertzsprung–Russell Diagram Branches



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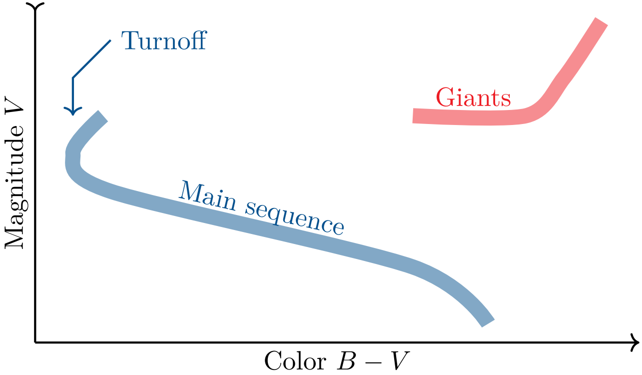

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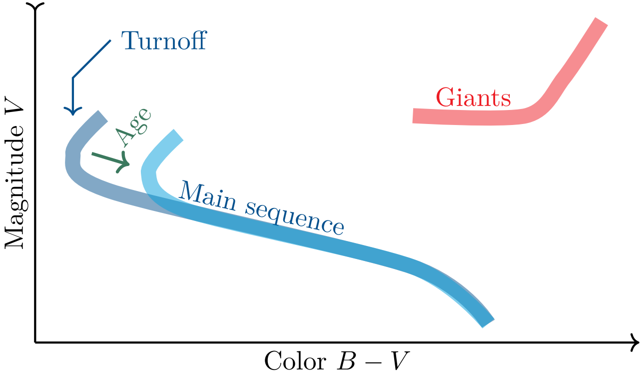

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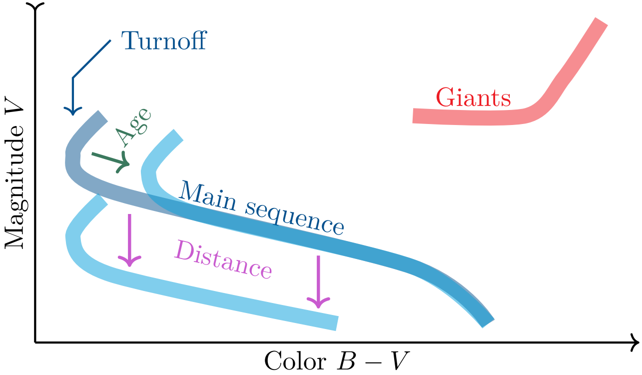

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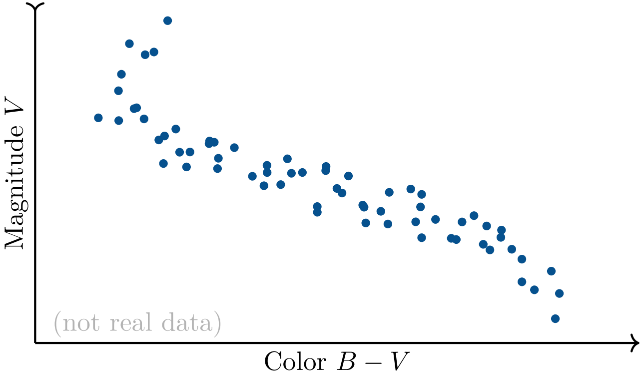

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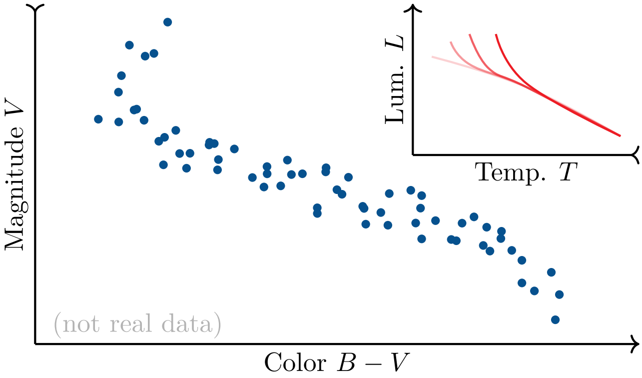

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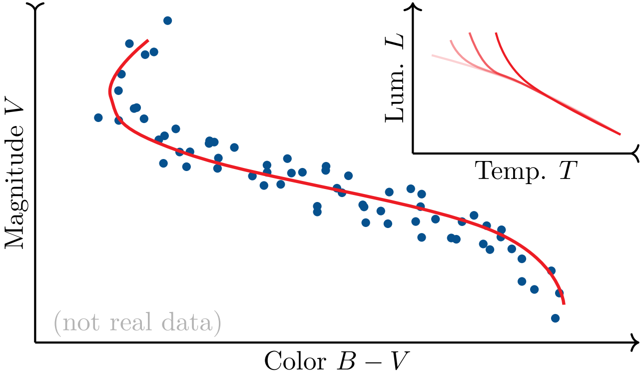

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Yes. . .

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Yes. . . However. . .

Methods: Extinction and Reddening

- Only two parameters? “There is another!”[1]

[1] Master Yoda, Star Wars: Episode V (1980).

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- Extinction from the interstellar medium:
  - → Reduces the luminosity (*i.e.* increases the V magnitude)
  - → Reddening: higher absorption in blue (*i.e.* increases the $B-V$ color)
- “Degeneracy” between extinction, age and distance!

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- "Degeneracy" between extinction, age and distance!
- Extinction can be computed:
  - → 3D dust map `Bayestar` (Green et al., 2019)
  - → Implemented in the `dustmap` python package (Green, 2018)

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- Not so good distance estimation ⇒ huge extinction variations
- Solutions:
  - → Using a literature distance to estimate the age
  - → Using a literature age to estimate the distance
  - → Extinction is an adjusting parameter in both cases

Results: Age and Distance of M 3, M 11 and M 37

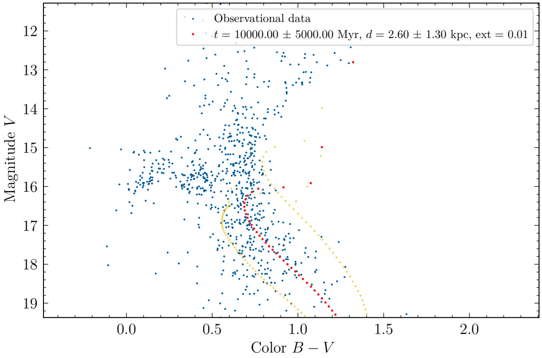

Figure 9: Best fit for M 3.

Results:

- Age: 10 ± 5 Gyr
- Dist.: 2.6 ± 1.3 kpc
- Ext.: ≤ 0.01 mag

Literature[1]:

- Age: 11.39 Gyr
- Dist.: 10.4 kpc
- Ext.: (negligible)

[1] Forbes &Bridges (2010); Paust et al. (2010)

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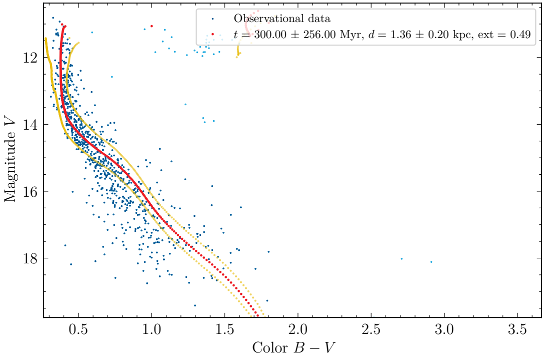

Figure 10: Best fit for M 11.

Results:

- Age: 300 ± 256 Myr
- Dist.: 1.4 ± 0.2 kpc
- Ext.: 0.49 ± 0.05 mag

Literature[2]:

- Age: 282 ± 49 Myr
- Dist.: 1.8 ± 0.3 kpc
- Ext.: 0.47 ± 0.03 mag

[2] Perren et al. (2015)

Results: Age and Distance of M 3, M 11 and M 37

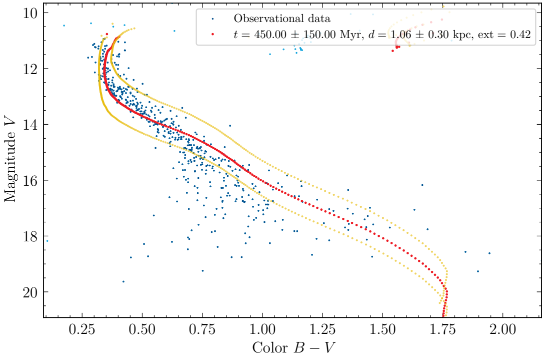

Figure 11: Best fit for M 37.

Results:

- Age: 450 ± 150 Myr
- Dist.: 1.1 ± 0.3 kpc
- Ext.: 0.42 ± 0.02 mag

Literature[3]:

- Age: 485 ± 28 Myr
- Dist.: 1.49 ± 0.12 kpc
- Ext.: 0.26 ± 0.04 mag

[3] Hartman et al. (2008)

Conclusion and Discussion

- Age and distance of M 11 and M 37 are in agreement with literature

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  - → Further away ⇒ Magnitude near detection limits
  - → Stars are not well resolved in globular cluster core
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- Application: This study of clusters combined with models of X-ray emission ⇒ Synthetic X-ray luminosity functions

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Figures and Credits

Fig. 1. 2T36 Archive, 2023, *M 11* (modified).
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Fig. 3. *Own work*, 2024.
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Acknowledgements / Remerciements

Merci à Christian M. Boily et Patrick Guillout d'avoir supervisé ce stage ainsi qu'à Simon Perrier pour sa participation, Lucile Rosoli et Frédérick Alland pour avoir ajusté des courbes à la main et enfin à Fabien Castillo pour son fichier de configuration SExtractor et sa compétence à différencier un $\log_{10}$ d'un ln sur une courbe en moins de 3 s.

Formation of Star Clusters

Figure 12: Formation of a star cluster.

- Jeans length:

$$L_{\mathrm{J}} = \left(\frac{3\pi}{32} \frac{\sigma^2}{G\rho} \right)^{1/2}$$

where σ is the speed dispersion and ρ the density.

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Figure 13: N-body problem.

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Figure 14: Stellar evolution problem.

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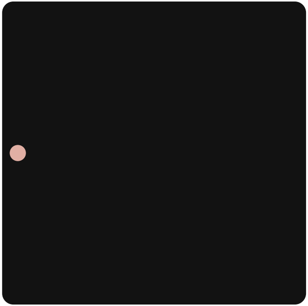

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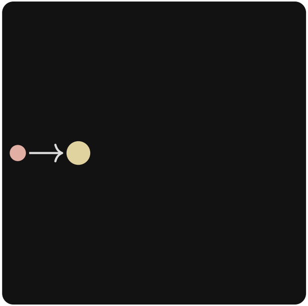

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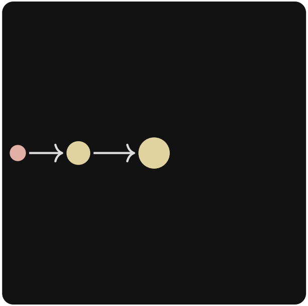

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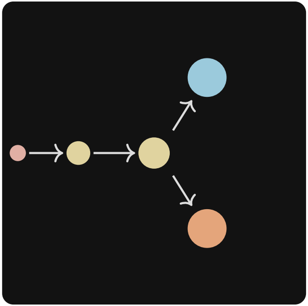

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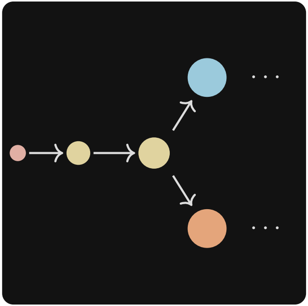

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Simulation of a Star Cluster: Workbench

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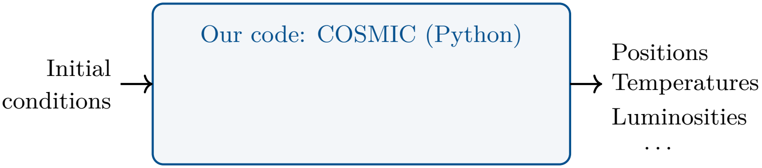

Figure 15: Principle diagram of the code.

[1] Portegies Zwart et al. (2009, 2013); Portegies Zwart &McMillan (2018); Pelupessy et al. (2013)
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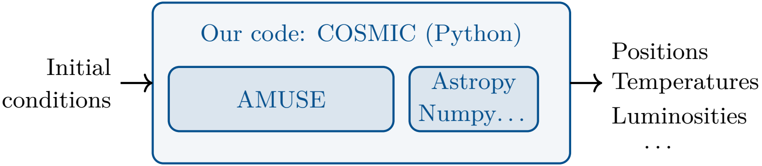

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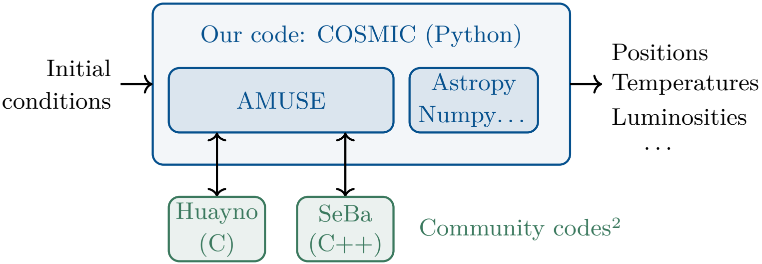

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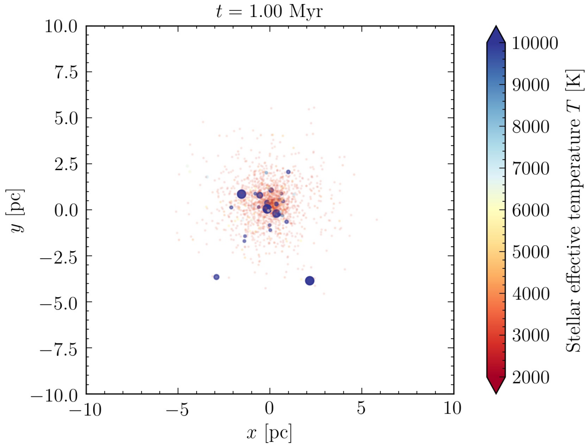

Figure 16: Simulation example with the COSMIC code.

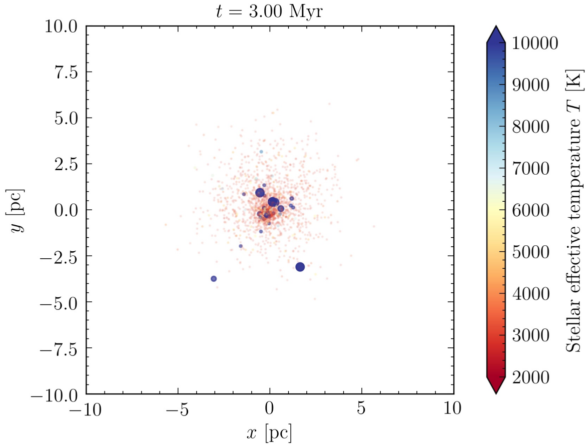

Figure 16: Simulation example with the COSMIC code.

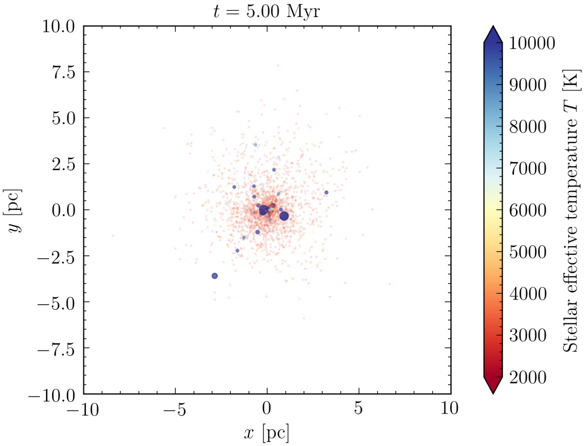

Figure 16: Simulation example with the COSMIC code.

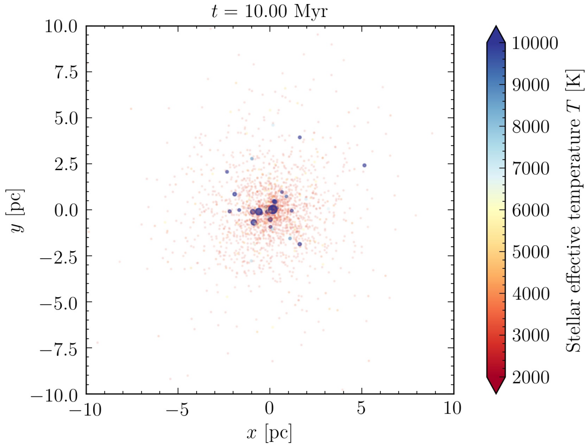

Figure 16: Simulation example with the COSMIC code.

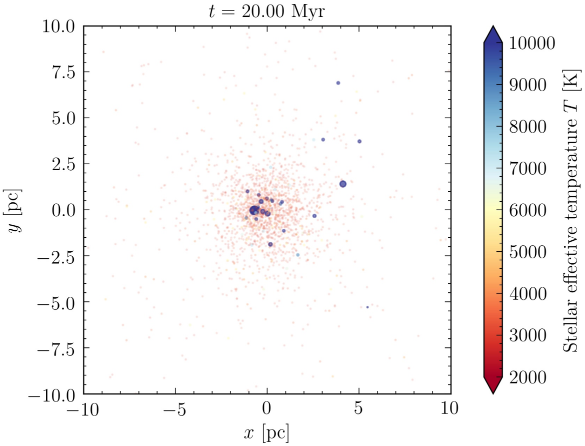

Figure 16: Simulation example with the COSMIC code.

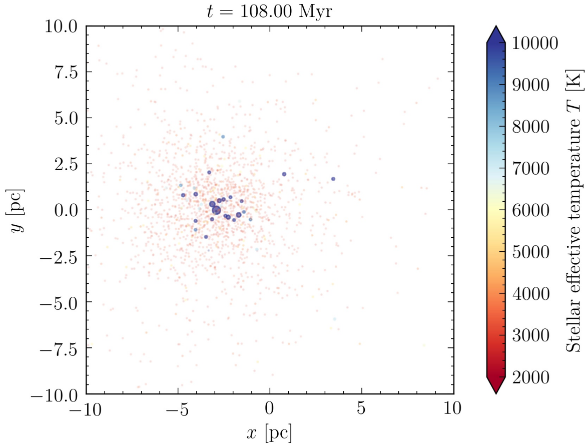

Figure 16: Simulation example with the COSMIC code.

Initial Conditions

- Salpeter's law:

$$\frac{\mathrm{d}N}{\mathrm{d}m} = m^{-2.35}$$

- Plummer's law:

$$\rho \propto \left(1 + \frac{r}{r_\mathrm{c}}\right)^{-5/2}$$

- King's model:

$$\rho \propto \left\{ \left[1 + \left(\frac{r}{r_\mathrm{c}}\right)^2\right]^{-1/2} - \left[1 + \left(\frac{r_\mathrm{t}}{r_\mathrm{c}}\right)^2\right]^{-1/2} \right\}^2$$

Salpeter's model and King's law

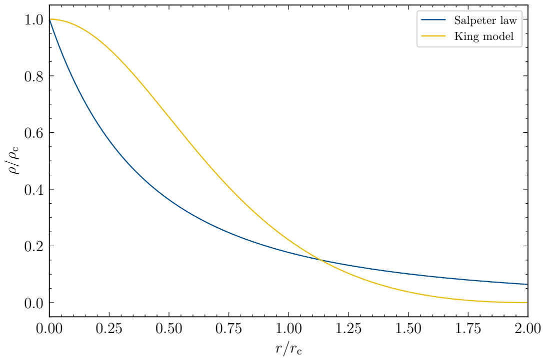

Figure 17: Comparison between the Salpeter's model and the King's law.

Relations

- Radius-Mass-Luminosity:

$$\frac{R}{R_\odot} \sim \left(\frac{M}{M_\odot}\right)^{1/3} \quad ; \quad \frac{L}{L_\odot} \sim \left(\frac{M}{M_\odot}\right)^{3.45}$$

- Magnitude:

$$m_i - m_{i,\mathrm{ref}} = -2.5\log_{10}\left(\frac{f_i}{f_{i,\mathrm{ref}}}\right) \quad ; \quad m_i - M_i = 5\log_{10}\left(\frac{d}{d_{\mathrm{ref}}}\right)$$

$$M_{\mathrm{bol}} = M_i + \mathrm{BC}_i = M_{\mathrm{bol},\odot} - 2.5\log_{10}\left(\frac{L}{L_\odot}\right)$$

- Extinction:

$$(M_i - M_j)_{\mathrm{cor}} = (M_i - M_j)_{\mathrm{obs}} - E(M_i - M_j) \quad ; \quad M_{i,\mathrm{cor}} = M_{i,\mathrm{obs}} - A_i$$

$$R = \frac{A_i}{E(M_i - M_j)} = 3.1 \text{ (in the Milky Way)}$$

Bessel B, V and R Filters

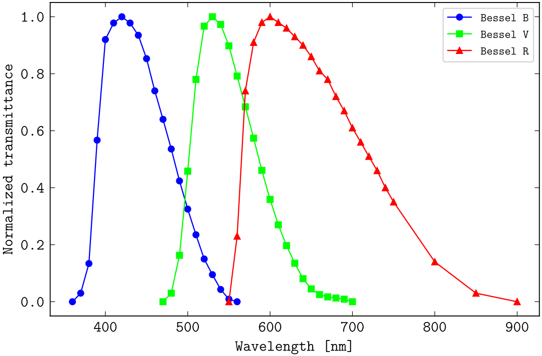

Figure 18: Bessel B, V and R filters.

List of Archive Observations

- NGC 5272 — M 3 (low quality, framing)
- NGC 6705 — M 11 (high FWHM)
- NGC 6205 — M 13 (bad quality)
- NGC 2099 — M 37
- NGC 5024 — M 53 (R magnitude calibration issue)
- NGC 6779 — M 56 (R magnitude calibration issue)
- NGC 6341 — M 92
- NGC 5466 (R magnitude calibration issue)
- NGC 6366 (R magnitude calibration issue)
- NGC 6633
- NGC 6939 (source extraction issue)

Observation of a Star Cluster: Data Reduction

Raw images:

- Background noise (camera thermal noise, cosmic rays,. . .)
- Optical defects (dust, vignetting, . . .)
- Signal (the image we want)

Observation of a Star Cluster: Data Reduction

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- Background noise (camera thermal noise, cosmic rays,. . .)
- Optical defects (dust, vignetting, . . .)
- Signal (the image we want)

Solutions:

- Calibration with *darks* and *flats*

$$\text{Signal} = \frac{\text{Raw} - \text{Dark}}{\text{Flat}}$$

Observation of a Star Cluster: Data Reduction

Raw images:

- Background noise (camera thermal noise, cosmic rays,. . .)
- Optical defects (dust, vignetting, . . .)
- Signal (the image we want)

Solutions:

- Calibration with *darks* and *flats*
- Multiple images aligned and stacked together

$$\text{Signal} = \sum \frac{\text{Raw} - \text{Dark}}{\text{Flat}}$$

Calibration of M 3

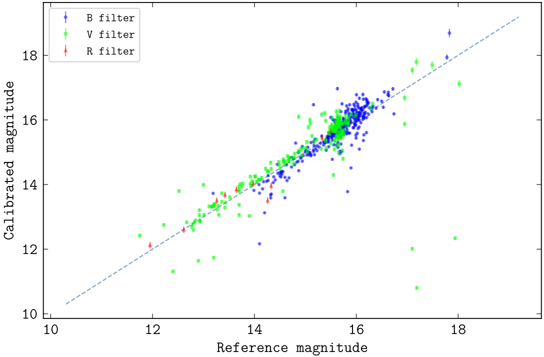

Figure 19: Calibration of M 3.

Calibration of M 3

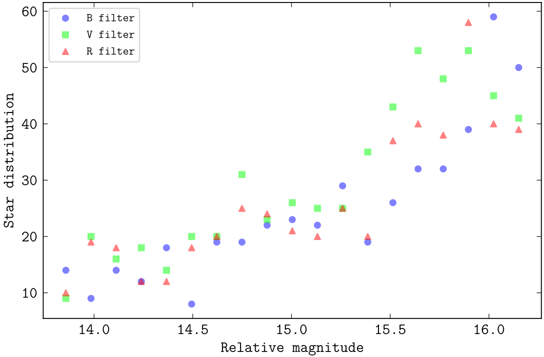

Figure 19: Calibration of M 3.

Calibration of M 3

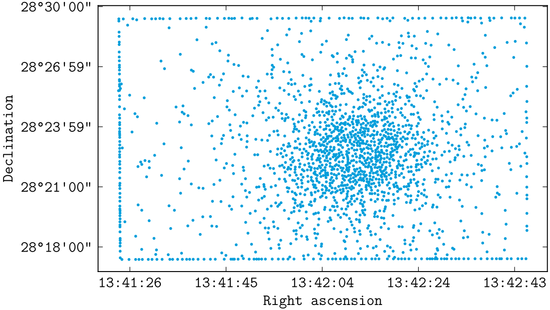

Figure 19: Calibration of M 3.

Calibration of M 11

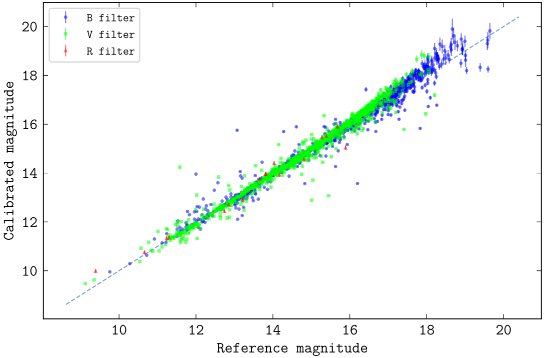

Figure 20: Calibration of M 11.

Calibration of M 11

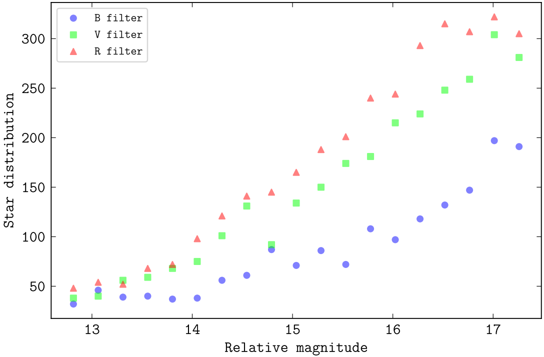

Figure 20: Calibration of M 11.

Calibration of M 11

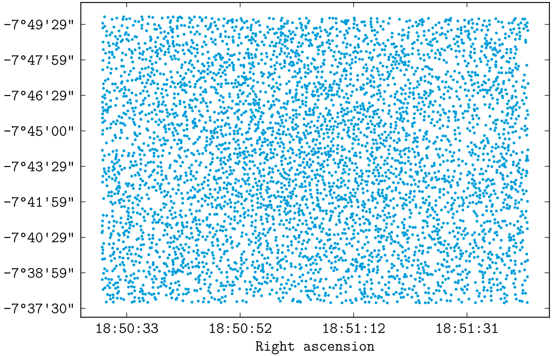

Figure 20: Calibration of M 11.

Calibration of M 37

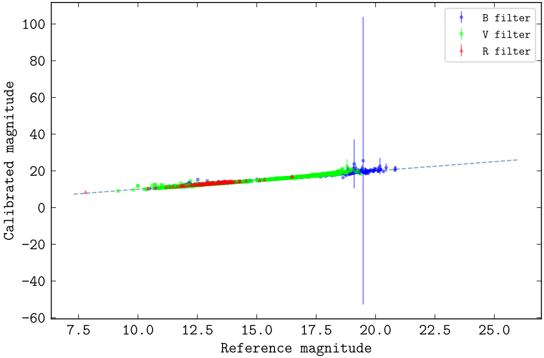

Figure 21: Calibration of M 37.

Calibration of M 37

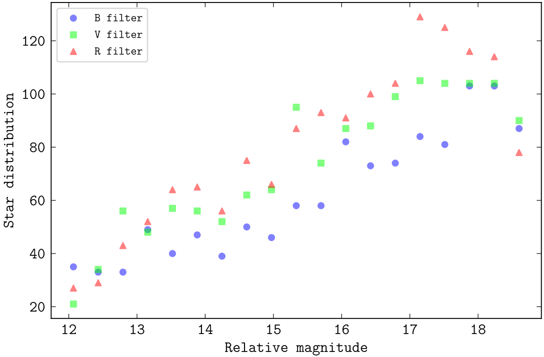

Figure 21: Calibration of M 37.

Calibration of M 37

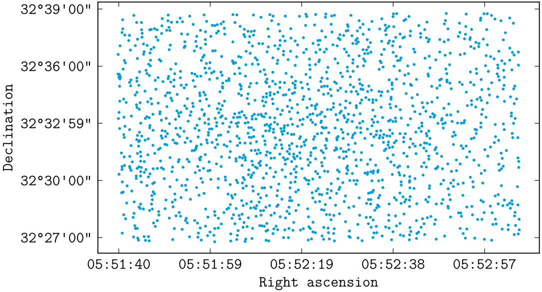

Figure 21: Calibration of M 37.

M 3 Extinction

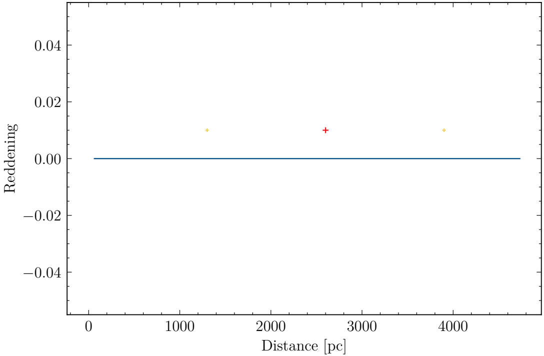

Figure 22: Fitted Extinction for M 3 and `Bayestar` values.

M 11 Extinction

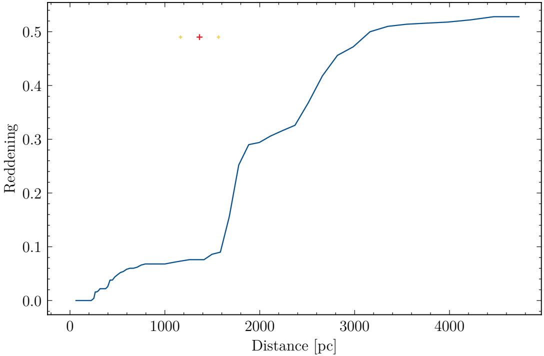

Figure 23: Fitted Extinction for M 11 and `Bayestar` values.

M 37 Extinction

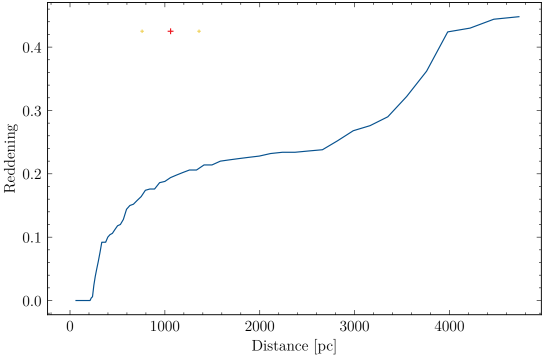

Figure 24: Fitted Extinction for M 37 and `Bayestar` values.