Rotating stars in the young open cluster M11

Beomdu Lim
Kyung Hee University

Gregor Rauw, Yael Naze (ULg)
Hwankyung Sung (SU)
Narae Hwang, and Byeong-Gon Park (KASI)
Pasquini et al. (2012) 
Mackey & Nielsen (2007)
Age spread

1\textsuperscript{st} generation

Gas retention

1\textsuperscript{st} + 2\textsuperscript{nd} generations

Donors,
Asymptotic Giant Branch stars?
Stellar rotation

I. Rotational mixing

- Rotating stars
- Non-rotating stars

Main sequence lifetime

II. Gravity darkening

- Higher temperature
- Higher luminosity
- Lower temperature
- Lower luminosity
Distance

Underlying distributions
Discovery of eMSTO in Messier 11

Possible factors
- Photometric errors
- Binary star population
- Differential reddening

The observed eMSTO is a genuine feature!

$\omega = 0.7$
$\tau = 200 \text{ Myr}$  $\tau = 250 \text{ Myr}$  $\tau = 400 \text{ Myr}$
MMT/Hectochelle (2017A)
\[ \frac{\lambda}{c} \sigma_1 V \sin i = 0.66, \text{ Gray (2005)} \]
Random error

\[ U - V = 0.4706 \pm 0.0218 + 0.0004 \pm 0.001 V_{eq} \sin i \]
Underlying distributions

Case 1: uniform dist. of $V_{eq}$ and uniform dist. of $i$

Case 2: uniform dist. of $V_{eq}$ and Gaussian dist. of $i$

Case 3: skewed dist. of $V_{eq}$ and uniform dist. of $i$

Case 4: skewed dist. of $V_{eq}$ and Gaussian dist. of $i$
Case 1: 6.2 ± 4.0 %
Case 2: 42.1 ± 13.2 %
(Best-fit $i_{\text{peak}} = 54 \pm 1^\circ$)
Case 3: 10.7 ± 4.6 %
Case 4: 74.1 ± 12.8 %
(Best-fit $i_{\text{peak}} = 50 \pm 2^\circ$)
Simple stellar population model

Stellar evolution model

$V_{eq}$, $i$, mass

$T_{\text{eff}}$ and $L_{\text{bol}}$

Gravity darkening

Differential reddening

Color and V mag
A simple stellar population

Stellar rotation
Extended main sequence turn-off originating from a broad range of stellar rotational velocities

Beomdu Lim1,2,*, Gregor Rauw1, Yaël Nazé1, Hwankyung Sung2, Narae Hwang3,4 and Byeong-Gon Park4,5

Star clusters have long been considered to comprise a simple stellar population, but this paradigm is being challenged, since in addition to multiple populations in Galactic globular clusters6, a number of younger star clusters exhibit a significant colour spread at the main sequence turn-off8–10. A sequential evolution of multiple generations of stars formed over 100–200 Myr is a natural explanation of this colour spread10. Another approach to explain this feature is to introduce the effect of stellar rotation11. However, its effectiveness has not yet been proven due to the lack of direct measurements of rotational velocities. Here, we report the distribution of projected rotational velocities (v \(_{\text{rot}}\)) of stars in the Galactic open cluster M11, measured by Fourier transform analysis. Cluster members display a broad distribution of rotational velocities, including Be stars, have redder colours than slow rotators. Monte Carlo simulations infer that cluster members have highly aligned spin axes and a broad distribution of equatorial velocities biased towards high velocities. Our synthetic cluster simulation further demonstrates how stellar rotation affects the colours of cluster members, suggesting that the colour spread observed in populous clusters can be understood in the context of stellar evolution without introducing multiple stellar populations.

STAR CLUSTERS

Stars in M11 Hide Their True Colors

THE WILD DUCK CLUSTER — or Messier 11 (M11) — is one of the most enticing telescopic sights in the summer. There are some 2,900 stars here, a rich assemblage of suns that for some resembles a flock of ducks in flight. Astronomers have long believed that all the stars in an open cluster such as M11 were born in a single generation and therefore should be close in age. But the Wild Duck presents a mystery. Stars of similar brightness (and presumably similar mass and, thus, evolutionary stage) display different colors, which are generally a good indicator of age.

To get to the bottom of this mystery, Beomdu Lim (Kyung Hee University, South Korea) and colleagues examined the spectra of stars in M11. To their surprise, it isn't the stars' ages that cause the spectral variety but their rotation. Spectra revealed that the stars are spinning at different rates. This range of spins leads to differences in star color and ultimately stellar lifetimes.

"The effects of rotation on stellar evolution were often neglected in the past," says study co-author Yaël Nazé (University of Liège, Belgium). The team published their findings November 5th in Nature Astronomy.

Most of a star's life is spent on the main sequence burning hydrogen (see page 14). When its core hydrogen is exhausted, the star switches and burning strategies, causing it to expand, redden, and leave the main sequence.

But the faster a star spins, the better it mixes hydrogen into its core, so the longer it can remain on the main sequence — 15% to 62% longer than its slower-rotating cousins of similar mass. Fast rotation also deforms the star. As its diameter expands, the equatorial regions cool and redden, appearing redder than slow rotators while still basking on the main sequence. The Wild Duck Cluster mimics two stellar populations when only one is expected.
Thank you!
\( \omega = 0.7 \)
\( \tau = 200 \) Myr
\( \tau = 250 \) Myr
\( \tau = 400 \) Myr

\( \omega = 0.0 \)
\( \tau = 160 \) Myr
\( \tau = 200 \) Myr
\( \tau = 320 \) Myr

\( \tau = 250 \) Myr
\( \omega = 0.3 \)
\( \omega = 0.5 \)
\( \omega = 0.95 \)