NGC 6791: A Review

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Presented to to the KITP “Galactic Archaeology and Precision Stellar Astrophysics” meeting in Santa Barbara, California

Thursday, 15 January 2015

Why You Should Feel Free To Interrupt Me

- I have 19 slides including this one, and we have an hour.
- I'm an NGC 6791 *groupie*, I am not an NGC 6791 *expert*.

NGC 6791 According to Wikipedia and according to Marc

- NGC 6791 is an open star cluster in the Lyra constellation. It was discovered by Friedrich August Theodor Winnecke in 1853. At roughly 8 billion years old, and with an Iron to Hydrogen abundance ratio that is more than twice that of the Sun, it is one of the oldest and most metal-rich clusters in the Milky Way. This is contrary to the typical rule-of-thumb where older means more metal-poor. Compounded with the fact that it has an unusually high population of stars, NGC 6791 is among the most studied clusters in the sky. - **Wikipedia**

- It's the only means we have to study stars that are common elsewhere in the universe – **Marc Pinsonneault**

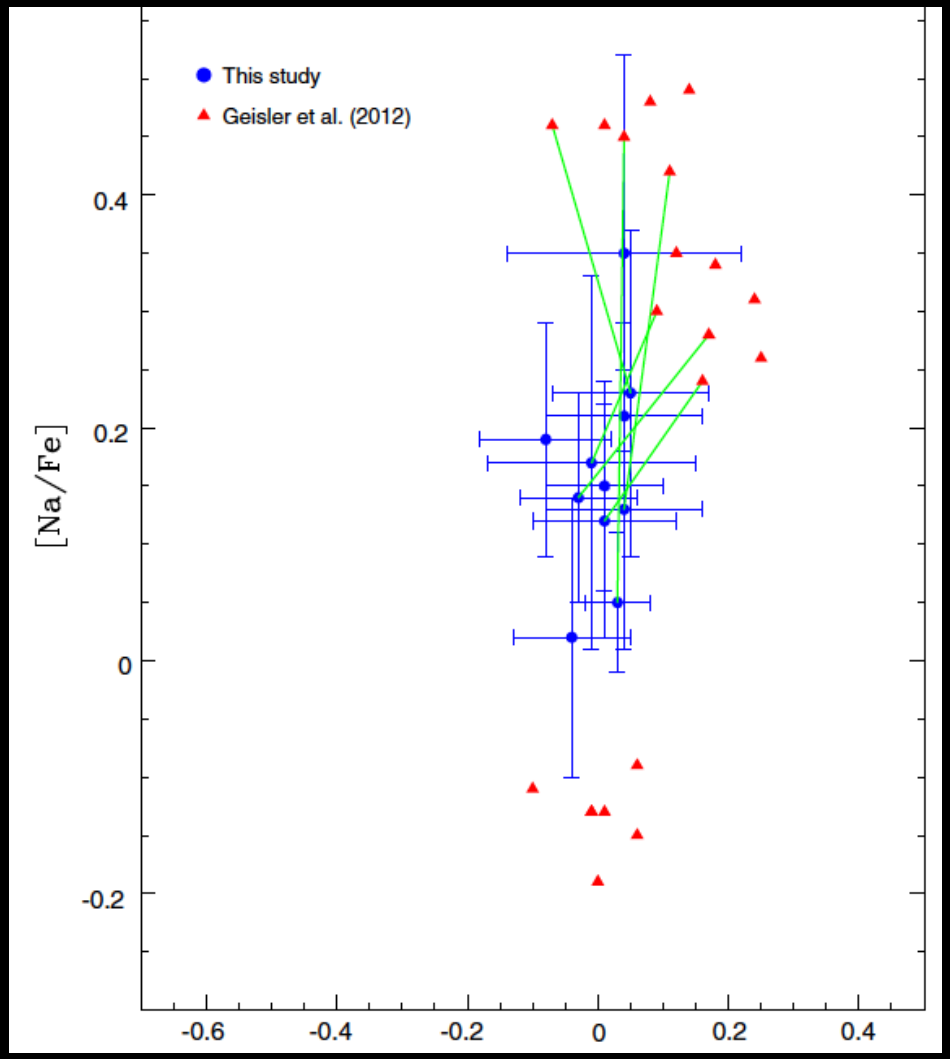
MGC 6791: Why It Matters

- The Mass of the cluster is 4000 $M_\odot$ and the population is old (t ≥≈ 8 Gyr), thus the cluster CMD is well-populated at all stages (MSTO, SGB, RGB, HB, WD, etc) making it a decent calibrator.
- Distance modulus is a modest μ≈13.2, extinction is intermediate, $A_V < 1.00$, thus it's observable !
- The metallicity is high, [Fe/H] ≈ + 0.35 or ≈2x solar, and thus it may be a calibrator of metal-rich ellipticals.
- It has multi-band photometry, detached eclipsing binaries, Kepler asteroseismology, high-res spectroscopy … in principal we can determine everything.

Metallicity of NGC 6791

- **Cunha et al.** (2015ApJ...798L..41C), with APOGEE H-band spectroscopy of 11 red giants: **[Fe/H]=+0.34**, [O/Fe]=+0.01, [Na/Fe]=+0.17, all homogeneous.
- **Boesgaard et al.** (2014arXiv1412.8515B), with Keck/HIRES spectra of 8 turnoff stars: **[Fe/H]=+0.30**, [O/Fe]=−0.06, [Mg/Fe]=+0.08, [Si/Fe]=+0.07, [Ca/Fe]=−0.13, [Ti/Fe]=-0.05, [Cr/Fe]=+0.05, [Ni/Fe]=+0.04.
- **Bragaglia et al.** (2014ApJ...796...68B), with 15 Keck/HIRES spectra of MSTO+RGB stars: **[Fe/H]=+0.33**, [C/Fe]=+0.01, [N/Fe]=+0.13, [O/Fe]=−0.10, [Ca/Fe]=+0.01, [Ni/Fe]=+0.12, [Na/Fe]=+0.14.
- **Geisler et al.** (2012ApJ...756L..40G) claimed to find a sodium-oxygen anti-correlation, argument since refuted.
- **Brogaard et al.** (2011A%26A...525A...2B) with UVES spectroscopy of three detached eclipsing binaries along the main-sequence, measure **[Fe/H]=+0.29**.

No Abundance Dispersion within NGC 6791 (**Cunha et al.** 2015ApJ...798L..41C)



Metallicity of NGC 6791 Concluded

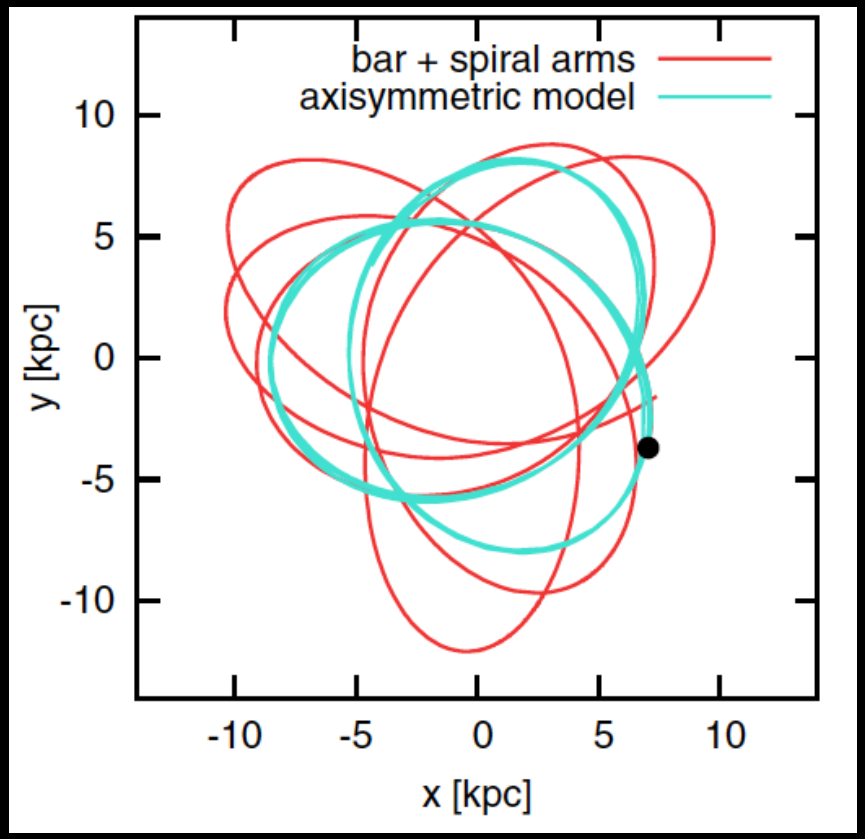
- The current consensus seems to be [Fe/H]≈+0.30-+0.35, or twice the solar metallicity.
- Metallicity may be a little higher along the red giant branch, where the prediction from stellar models of diffusion is (Δ[Fe/H]≈0.06 dex).
- No evidence for abundance variations within the cluster, cluster appears chemically homogeneous.
- The only element that convincingly appears to have a non-solar-scaled abundance is sodium, [Na/Fe]≈+0.15.

A comment on the metallicity of NGC 6791

- “How could something so metal-rich be so old? Shouldn’t older things be less metal-rich?” – Said a lot of people.
- But the Milky Way has inside-out formation, more metal-rich stars formed earlier in the inner Milky Way.
- Jilkova et al. (2012A%26A...541A..64J), with their simulations, find that the open cluster may have migrated outwards over the last few Gyr, but it’s hard to to be sure due to uncertainties in the Milky Way model – they say it’s of “very low” probability.

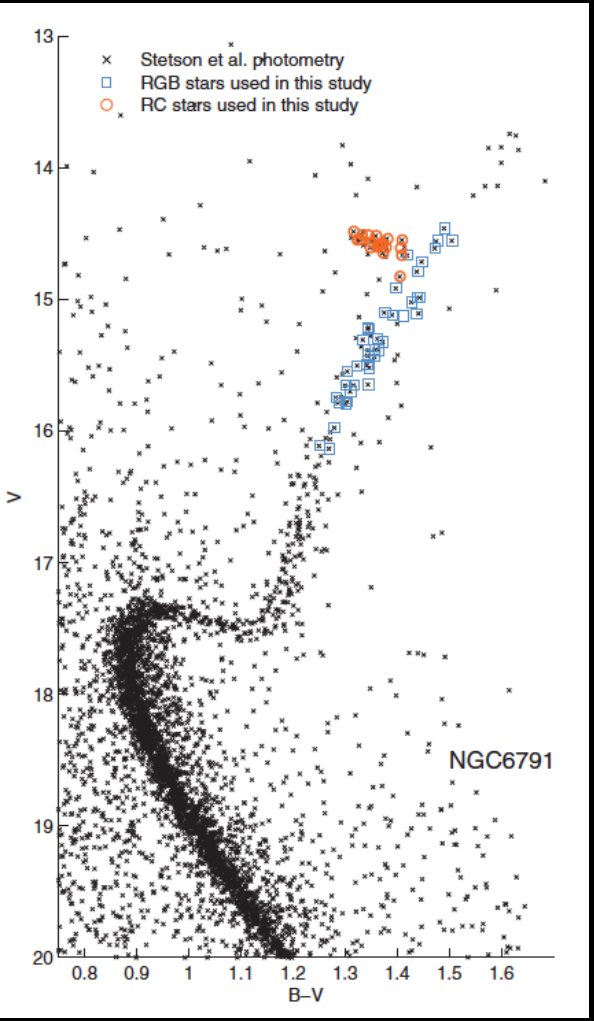
Can NGC 6791 radially migrate?

- Jilkova et al. (2012A%26A...541A..64J) say it's strongly dependent on the Galactic potential assumed.



Kepler Asteroseismology

- Miglio et al. (2012MNRAS.419.2077M) analyzed the Kepler photometry for 40 red giant branch stars and 19 red clump stars in the cluster.
- Mass-loss rate suggested of $\Delta M=0.09\pm0.03(stat)\pm0.04(sys)\ M_{\odot}$, consistent with a slightly low Reimer's mass-loss with $0.10\leq\eta\leq0.30$.



Kepler Asteroseismology Continued

- Caveat: the zero point of the mass-scale is enhanced by ≈7%. Miglio et al. measure an asteroseismic mass of M = 1.23±0.02 $M_\odot$, higher than the empirical value of M=1.15±0.02 $M_\odot$.
- Brackets an offset of ΔM=0.17 $M_\odot$ of identified by Epstein et al. (2014ApJ...785L..28E) at low metallicities.

$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{3/2},$$

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{1/2}.$$

Kepler Asteroseismology of NGC 6791 Concluded

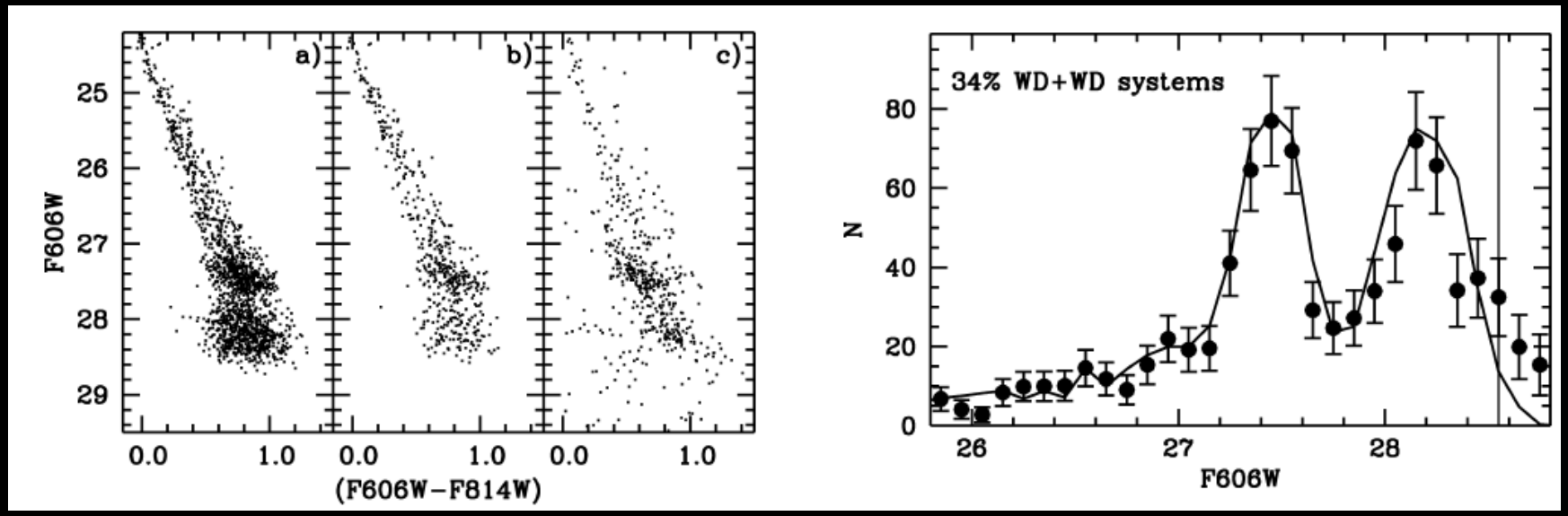
- Mass-loss between red giant branch and red clump is close to canonical model predictions, albeit a little low.

[editorial: This is unproblematic as the theory of red giant mass-loss is not very good].

- The Asteroseismic mass predictions are high, albeit only a little high, by 7%.

[editorial: In any other field a 7% offset at first data would be cause for celebrations. However, false prophets within the asteroseismic community have been peddling the promise of “model-independent” masses for years, giving this result the veneer of theoretical failure.]

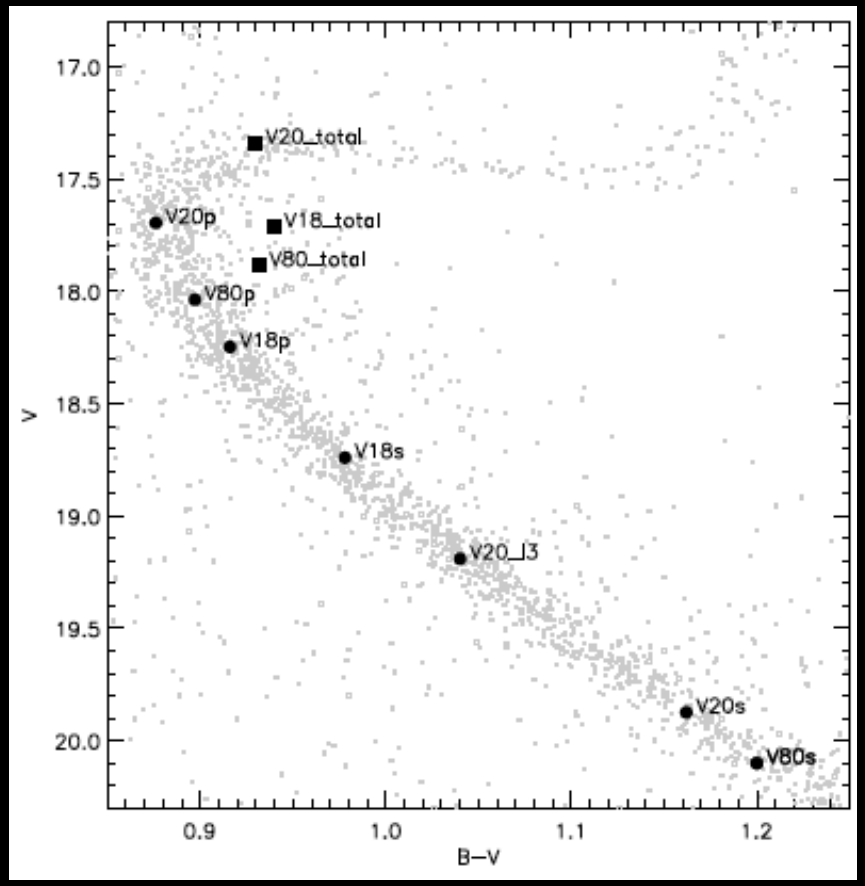
White dwarf cooling sequence of NGC 6791



- Bedin et al. (2008ApJ...678.1279B) showed that the two peaks give predicted ages of ≈4 and ≈6 Gyr, both are significantly lower than other age determinations… significantly lower than other determinations.
- Bedin et al. (2008ApJ...679L..29B) argue that the brighter peak is easily explained If ~34% of the cluster's stars are in binaries.

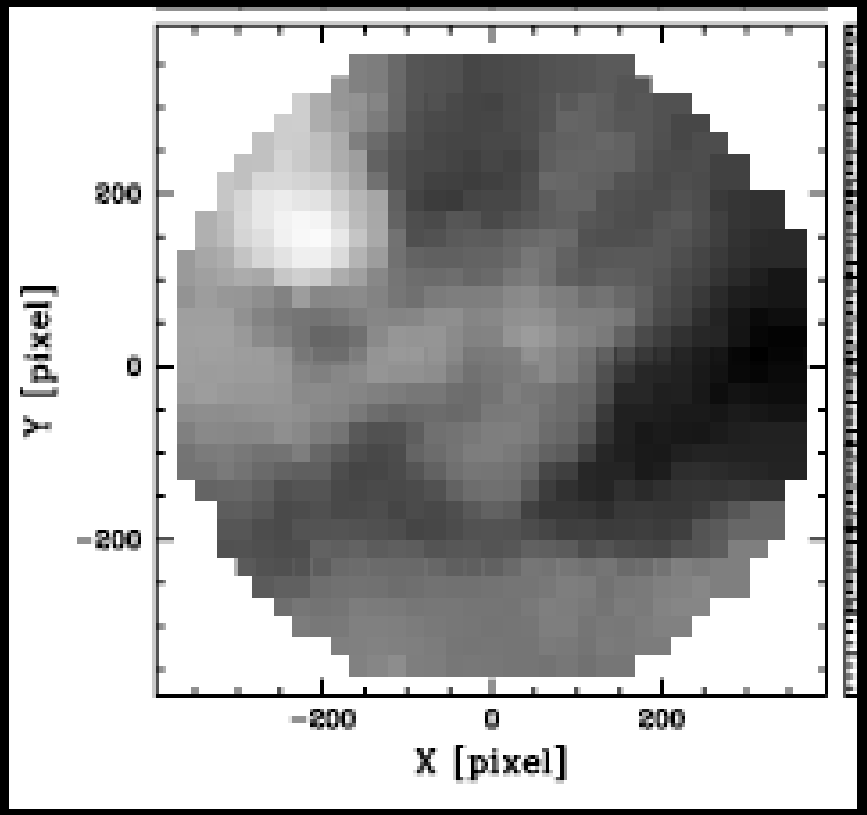
Detached Eclipsing Binaries in NGC 6791

- Brogaard et al. (2011A%26A...525A...2B) measure metallicities, masses, and radii for three eclipsing binaries on the main-sequence.
- These are powerful constraints on age, distance, reddening.



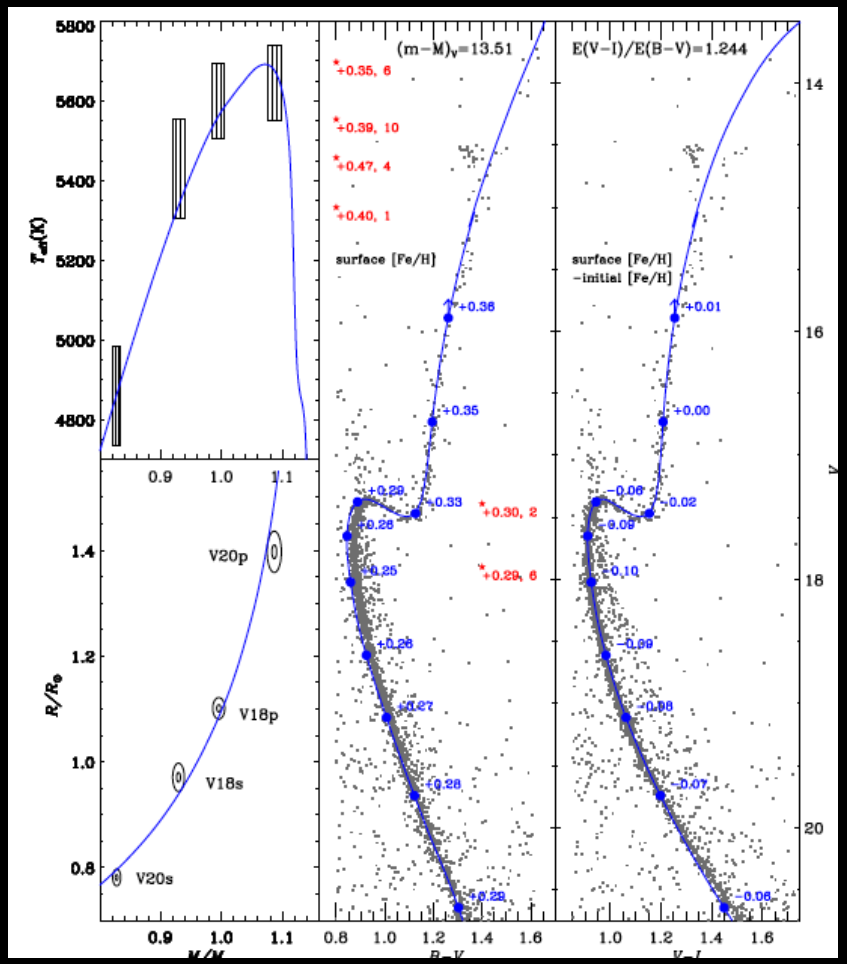
Detached Eclipsing Binaries and the Colour-Magnitude Diagram

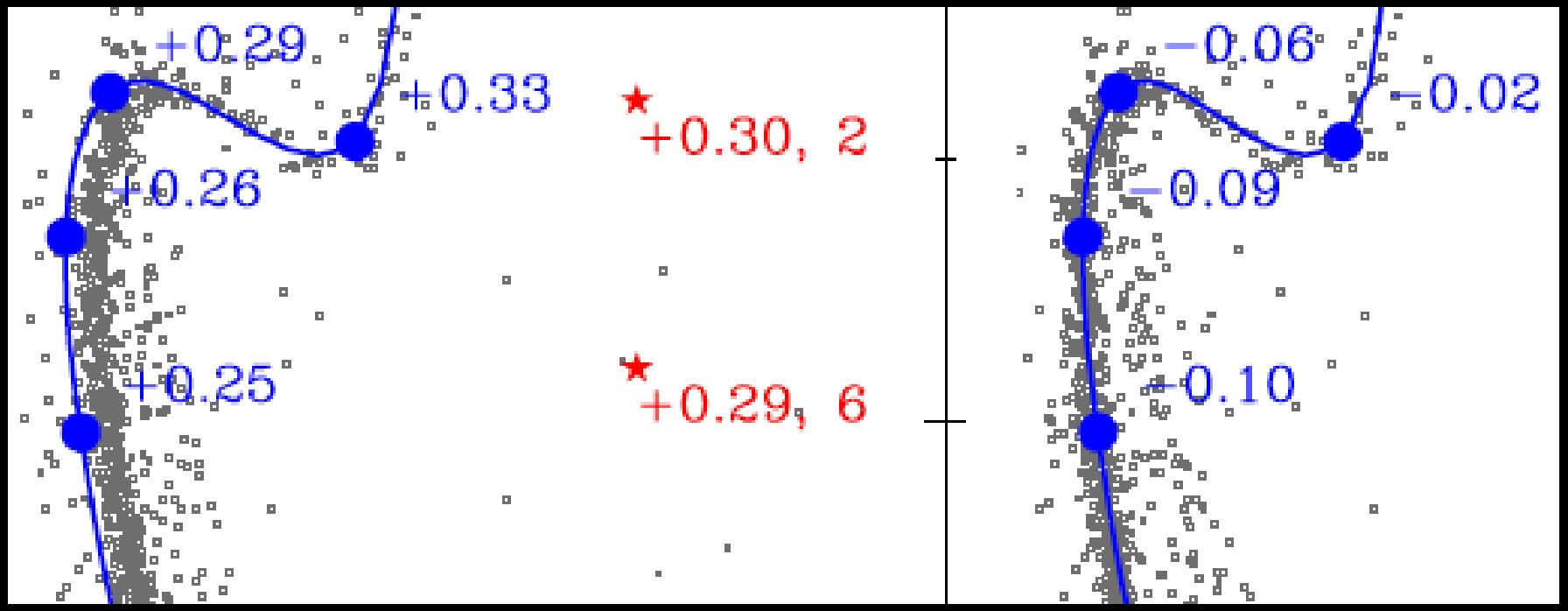
- Brogaard et al. (2012A%26A...543A.106B) jointly model the whole BVI reddening-corrected CMD and the detached Eclipsing binaries.
- Mass at the base of the RGB is M=1.15±0.02 $M_{\odot}$, independent of detailed model assumptions.
- T= 8.3 Gyr, Y=0.30, $(m-M)_V$=13.51, E(B-V)=0.14±0.01.



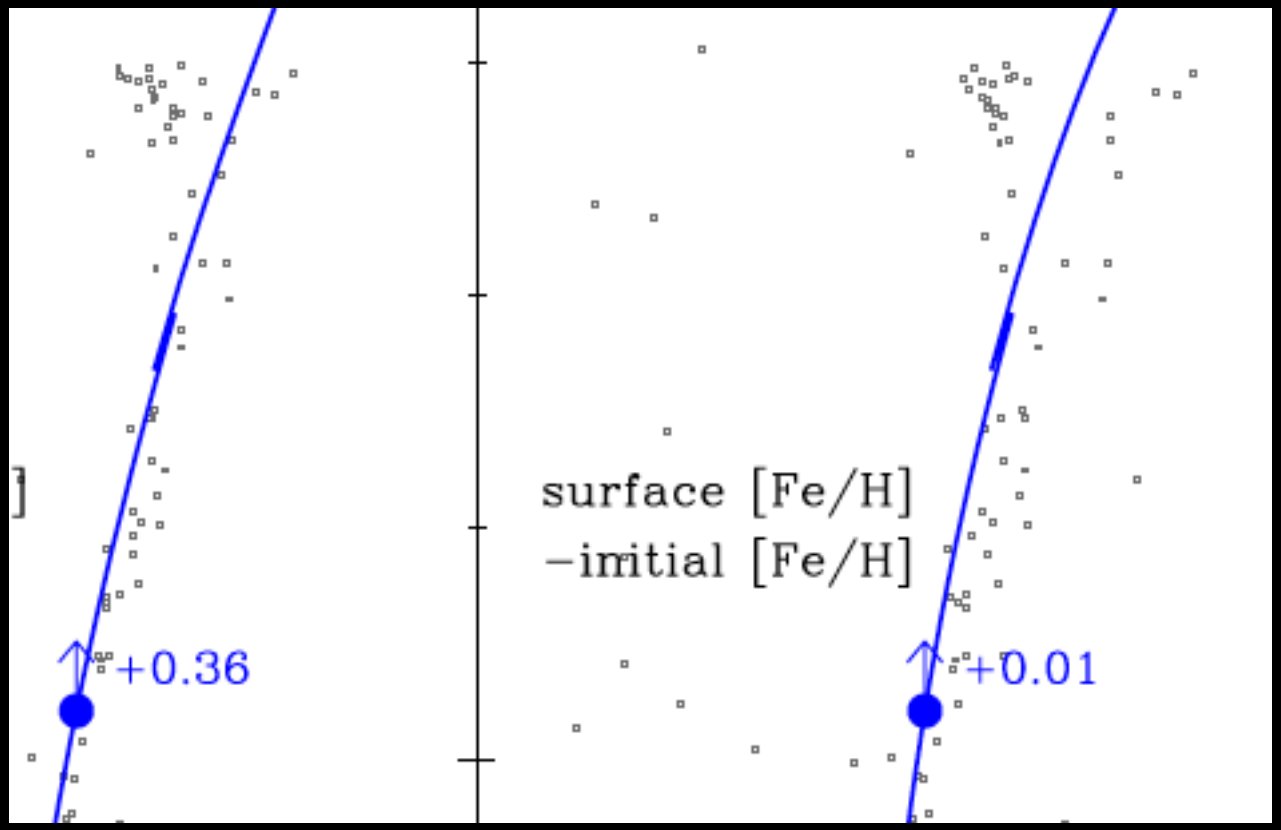
A Few Residual Difficulties In the Final Modelling

1. Reddening curve;
2. Diffusion;
3. Fitting the eclipsing binaries;
4. Helium and metallicity zero points;





(B-V) colour of the NGC 6791 turnoff is off by ≈0.03 mag.
Reddening error? Small metallicity offset? Helium?



V-I colour of the RGB is ≈0.05 mag redder than the isochrone at the luminosity of the RC. Reddening error? Small metallicity offset?

My Conclusions: A Lucid Picture of NGC 6791 is Emerging

- Some approximate truths: [Fe/H]≈+0.30, t≈8 Gyr, (m-M)V≈13.50, E(B-V)≈0.15, etc.
- Mystery #1: Do all elements other than Sodium plateau to |[X/Fe]|≤0.10 for [Fe/H]≥0.0? Should we care?
- Mystery #2: Why does the white dwarf sequence give an age underestimated by ≈25%?
- Mystery #3: Why are the asteroseismic masses overestimated by ≈7%?
- Mystery #4: What's the reddening curve toward NGC 6791? Does it matter?