THE INFRARED Ca II TRIPLET: A LUMINOSITY INDICATOR FOR STELLAR POPULATION SYNTHESIS

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ABSTRACT

We study the properties of the Ca II infrared triplet (Ca T) from a sample of Reticon spectra of 62 stars. The stars range over spectral types B through mid-M, and the sample spans some four orders of magnitude in gravity $g$, and almost a factor of 10 in metallicity. The stars in the sample have all been the subject of earlier high-dispersion model atmosphere studies.

Our major finding is that, over all spectral types, from F to mid-M, and over this large gravity interval, the equivalent width of Ca T, $W$(Ca T), correlates strongly with log $g$. Deviations of observed points from this relationship are weakly correlated with metallicity. We discuss for earlier stars the Paschen line contamination and for cooler ones the blend with TiO bands. Indeed, in the waveband around 8500, we find both a dwarf: giant discriminator, Ca T, and an indicator of the presence of cool stars, the TiO bands.

From the point of view of population synthesis, the log $g$: $W$(Ca T) relationship is fundamental since it is an almost one-valued relation, being relatively insensitive to metallicity. Thus, since most of the light from galaxies is thought to come from G and K stars, the Ca T feature should be a useful tool for constraining the dwarf: giant ratio of the light-dominant stellar population.

Existing measurements of Ca T in the nucleus of M31 indicate that the light in this region of the spectrum is giant dominated and that there is no evidence for any change in the old stellar population with radius in the innermost 30″ or so of the bulge. The Na I λ8190 measurements must therefore indicate a variation in some other parameter of the population such as metallicity.

Subject headings: galaxies: individual — galaxies: stellar content — infrared: spectra — stars: luminosities
The Stellar Assembly History of Galaxies

Decoding the fossil record

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Outline

• Data compression
• The fossil record
• Downsizing
• Environment dependence
Star Formation History – two complementary approaches

- Two general approaches:
- Look for signs of recent SF in galaxies at high z (e.g. UV) (e.g. Lilly et al 1996, Madau et al 1996; Ouchi et al 2003)
- Look at nearby galaxies and date the stars in them (“fossil record”)
- If Copernican Principle holds, they should agree
Sloan Digital Sky Survey

- ~400,000 spectra public in SDSS Data Release 4 (DR4)
- Final goal ~$10^6$ galaxy spectra

(Panter, Heavens & Jimenez (2003) analysed 37000 SDSS EDR galaxies)
Advantages of fossil approach

- Decouples star formation from mass assembly
- Not so sensitive to uncertain obscuration
- Get SFR for a wide range of cosmic time
- Small statistical errors
- Large galaxy samples
- Faint samples
Disadvantages of fossil approach

- Needs a good theoretical spectral synthesis model
- Redshift-time relation is sensitive to cosmology (but so are volume elements at high z)
- Poor time- and z-resolution at high z
Characterising the SFH

- Current models and data allow the **star formation rate** and **metallicity** to be determined in around 8-12 time bins
- **10 x 2 + 1 dust parameter** = 21 parameters – **significant technical challenge**
- To analyse the SDSS data would take ~200 years
- Needs some way to speed this up by a large factor
- We use MOPED
What is MOPED? (Tons of encouragement from Bernard)

• Massively Optimized Parameter Estimation and **Data Compression**
• **Extracts information from a compressed dataset**
• Compression is optimized to contain as much information about parameters which define data
• **Need to be able to model data to determine compression**
• **Information Compression Technique**

Lossless linear compression

Assume:

\[ L = \frac{1}{\| C \|^{1/2}} \exp \left\{ -\frac{1}{2} (x - \mu)^T C^{-1} (x - \mu) \right\} \]

where:

- \( x \) = data
- \( \mu \) = expected value of data, dependent on parameters (e.g. age)
- \( C \) = covariance matrix of data
- \( y = b \cdot x \) = new (compressed) dataset

\[ b_m = \frac{C^{-1} \mu_m - \sum_{q=1}^{m-1} (\mu^T_m b_q) b_q}{\sqrt{\mu_m C^{-1} \mu_m - \sum_{q=1}^{m-1} (\mu^T_m b_q)^2}} \]

= probability of parameters given the data, if priors are uniform

Lossless? Look at Fisher Matrix
What does this mean?

- A $\chi^2$ test requires $N_{\text{param}}$ calculations, not $N_{\text{pixels}}$
- Massive speedup possible
  - for Sloan with 2000 flux points, 2000/23 parameters
    ~100 times
- Allows us to explore any degeneracies on the hypersurface – Markov Chain Monte Carlo
- No fancy footwork (PCA) – Direct link to models
- Need to model the spectrum somehow...
Recovering Star Formation History from Sloan spectra

Markov Chain Monte Carlo method used to find best solution and marginal errors.
MCMC errors
MOPED results - Old Populations

- **Simple Galaxy**
- **Oldest component peaked at ~ 9 Gyr**
- **Burst of Star Formation at ~ 1 Gyr**
- **MCMC reveals no degenerate solutions**

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Things don’t always go so well...

- Broad young and old populations

- But we can still see it!

- MCMC chain reveals degenerate solutions (minimum three)

- On AVERAGE the correct SFH is recovered. (Panter, 2004)
3AA Examples: Old Galaxy 2 - $\chi^2 = 1.59$
How many bins do I need?
RESULTS

• Mass function
• Evidence for downsizing
• Mass-metallicity relation
• Assembly of dark matter
• Effects of environment
The mass function of SDSS galaxies over 5 orders of magnitude

The NO-evolution of the mass function

\[ \log_{10} \frac{M_s}{h^{-2} M_\odot} \]
Comparison to the Millenium Run
The mass-metallicity relation
SFR in galaxies of different stellar masses

- Split by mass

Stellar masses:

\[ >10^{12} \text{ M}_\odot \ldots < 10^{10} \text{ M}_\odot \]

Galaxies with more stellar mass now formed their stars earlier

(Curves offset vertically for clarity)
More tests. This time systematics of SDSS and theoretical models have been included.

**Models do matter**

**IMF does not matter**
How well are we fitting?
Star formation and dark matter assembly do not track each other

However, if only 6% of baryons in today’s dark halo are stars, then star formation efficiency at $z\sim2$ needs to be only 10% to account for the observed stellar mass from the fossil record. Even “slow” star formation from molecular clouds can do the job.

Jimenez et al. MNRAS 2005
Where are the galaxies today that were red and blue in the past?
To study environment use Mark Correlations

- Treat galaxies not like points, but use attributes (e.g. luminosity)
- Measure the spatial correlations of the attributes themselves
- A mark is simply a weight associated with a point process (e.g. a galaxy catalogue)

For example, use luminosity of galaxies.
SF as a function of environment (Mark Correlations)

Metallicity as a function of environment (Mark Correlations)

The Atacama Cosmology Telescope

\begin{equation}
\delta T = \frac{[(1+z)^3 - 1 - z]}{2m^2} \times \mu K
\end{equation}

- Diffuse SZ
- Ostriker-Vishniac
- Patchy Reionization

Multipole 1

100

10

1

10

10^4

9000

3000

Graph showing temperature fluctuations and their relation to multipole values.
Conclusions

- SDSS + MOPED measure past star formation rate from fossil record
- Useful observational data on stellar mass function/SFR of different galaxy types
- Most of the stars in massive galaxies ($M_*>10^{11} \, M_\odot$) already formed at $z\sim2$
- The main progenitor of today’s dark matter halo contains enough gas to form the observed stars
- Only 10% of available gas at high-z needs to be converted into stars
- Challenge then is to explain why so little gas is transformed into stars
- Mark correlations tell us the clustering of galaxies