# Chemical and Orbital Clues Behind the History of Globular Clusters

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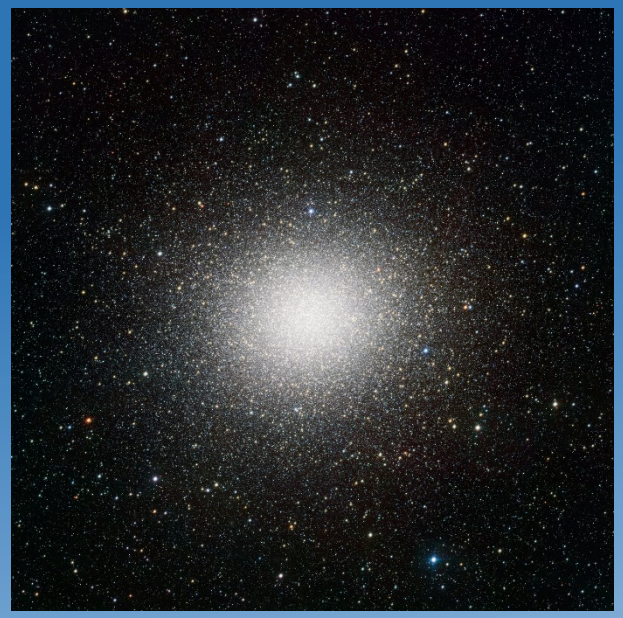
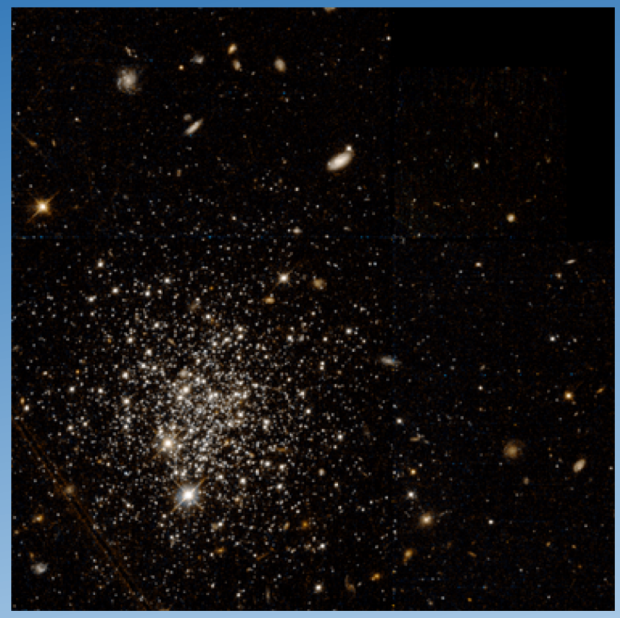
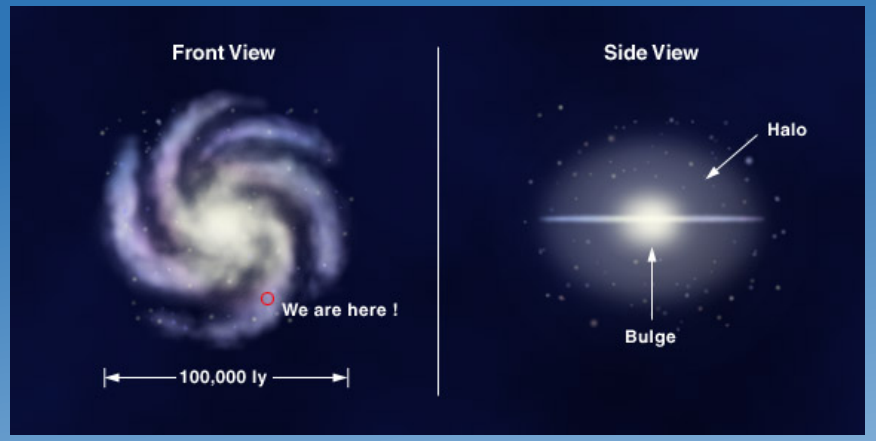


(ESO/INAF-VST/OmegaCAM)



(Arp-Madore 1/HST)

# What are Globular Clusters?




(Deep Skies Objects, www.lcsd.gov.hk)

"Globular Clusters are roughly spherical, densely packed groups of stars found around galaxies. They probably formed at the same time as their host galaxies, therefore they provide a unique fossil record of the conditions during the formation and early evolution of galaxies." (Ashman & Zepf, 1998)

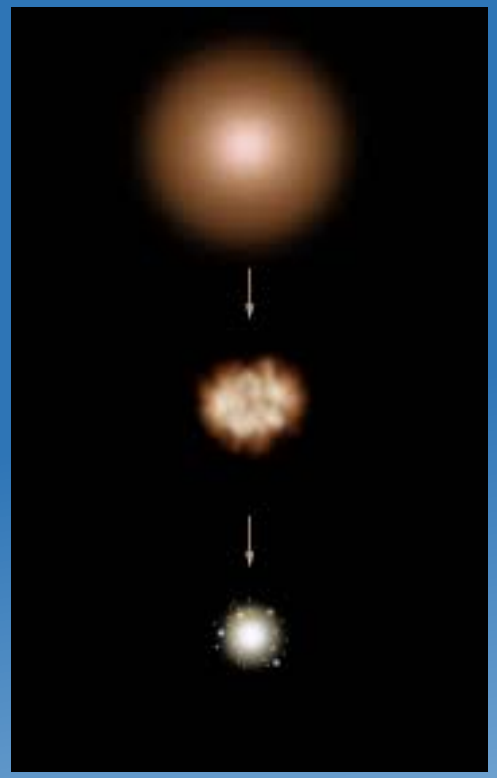
# What Can Globular Clusters Teach Us?

- Provide a fossil record of a galaxy's dynamical and chemical conditions during formation
- Constrain estimates on the minimum age of the universe
- Provide examples to compare different stellar populations
- Can be used to test models of galaxy formation and evolution

(Ashman & Zepf, 1998)

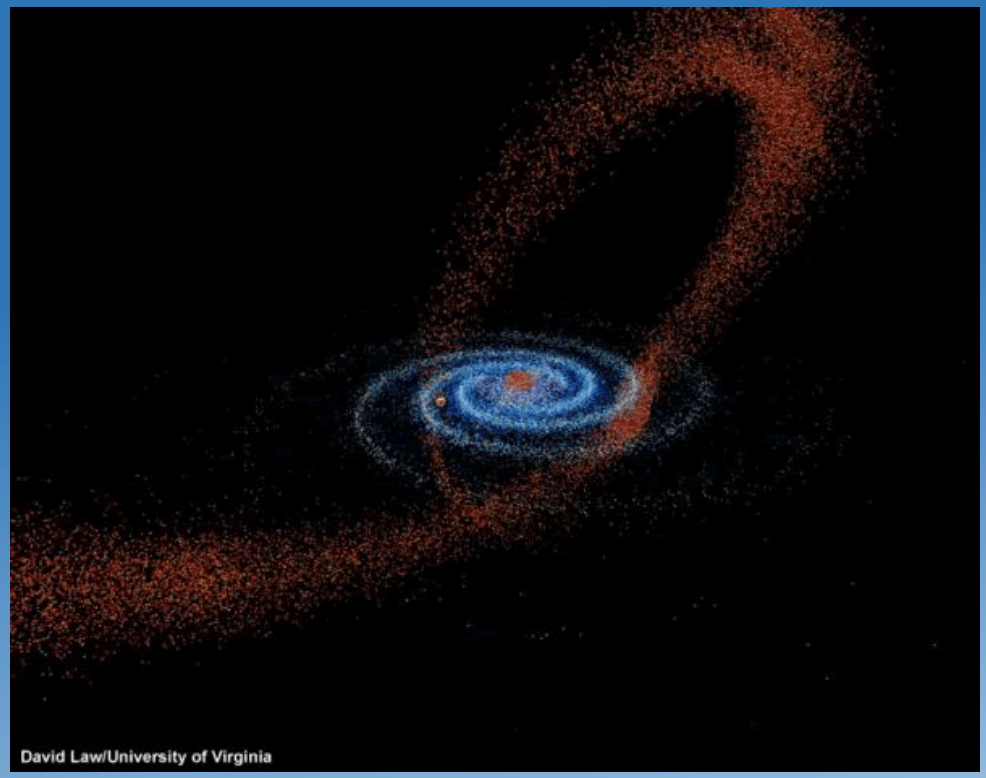
# How GC's fit into Galaxy Formation

Monolithic Collapse

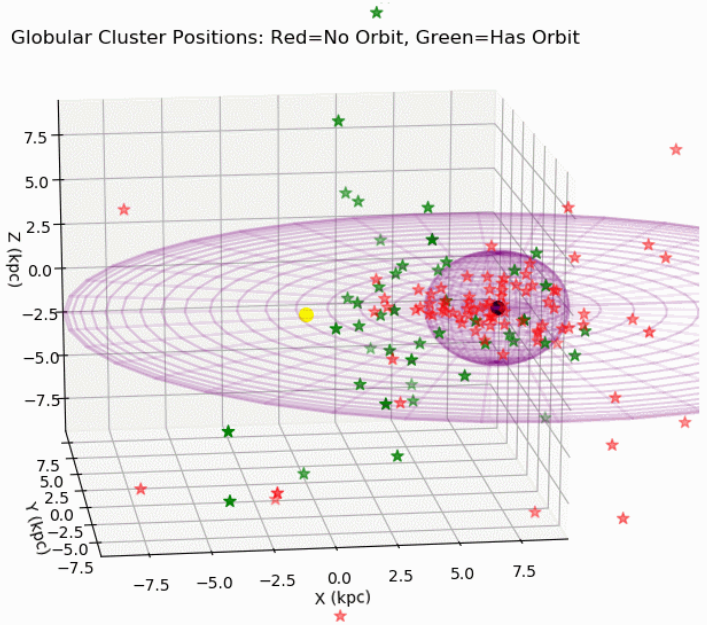


(P .McCarthy, OCIW)

Accretion



# The Model




- Metallicity: More Negative = Low Metallicity,

  More Positive = High Metallicity
- Age:  Higher Index = Older, Lower Index = Younger
- Energy: More negative = Lower energy, tightly bound,

  More positive = Higher energy, loosely bound

## Linear Regression Model

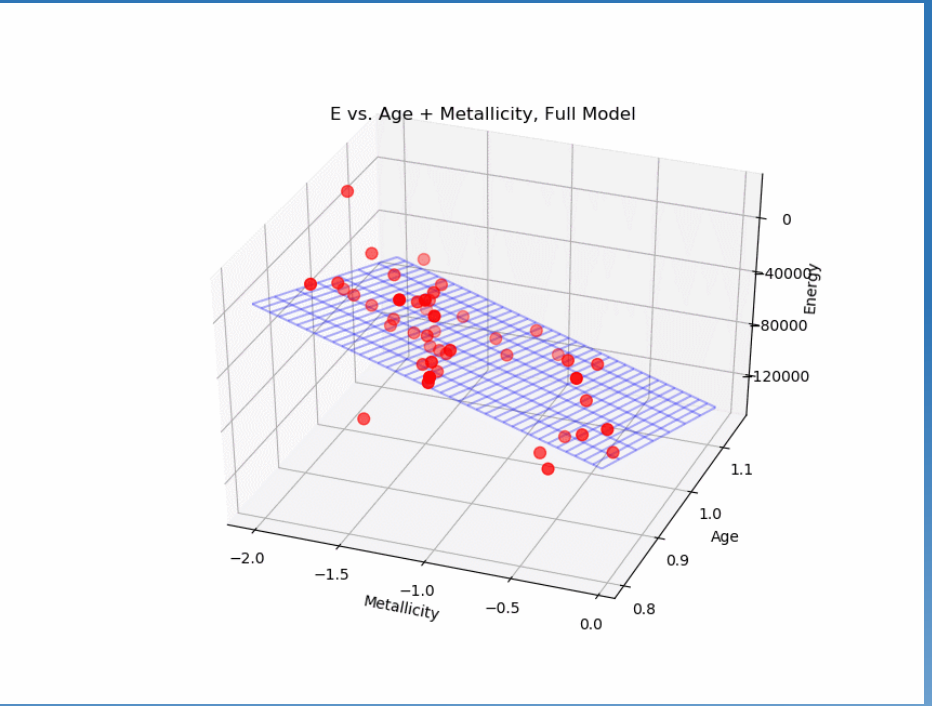
OLS Regression Results

| | | | |
|---|---|---|---|
| Dep. Variable: | E | R-squared: | 0.384 |
| Model: | OLS | Adj. R-squared: | 0.355 |
| Method: | Least Squares | F-statistic: | 13.69 |
| Date: | Mon, 23 Jul 2018 | Prob (F-statistic): | 2.39e-05 |
| Time: | 14:54:55 | Log-Likelihood: | -540.92 |
| No. Observations: | 47 | AIC: | 1088. |
| Df Residuals: | 44 | BIC: | 1093. |
| Df Model: | 2 | | |
| Covariance Type: | nonrobust | | |

| | coef | std err | t | P>\|t\| | [0.025 | 0.975] |
|---|---|---|---|---|---|---|
| Intercept | 1.029e+05 | 4.99e+04 | 2.060 | 0.045 | 2235.091 | 2.04e+05 |
| MetalZW | -3.857e+04 | 7933.320 | -4.862 | 0.000 | -5.46e+04 | -2.26e+04 |
| AgeZW | -2.131e+05 | 5.51e+04 | -3.869 | 0.000 | -3.24e+05 | -1.02e+05 |

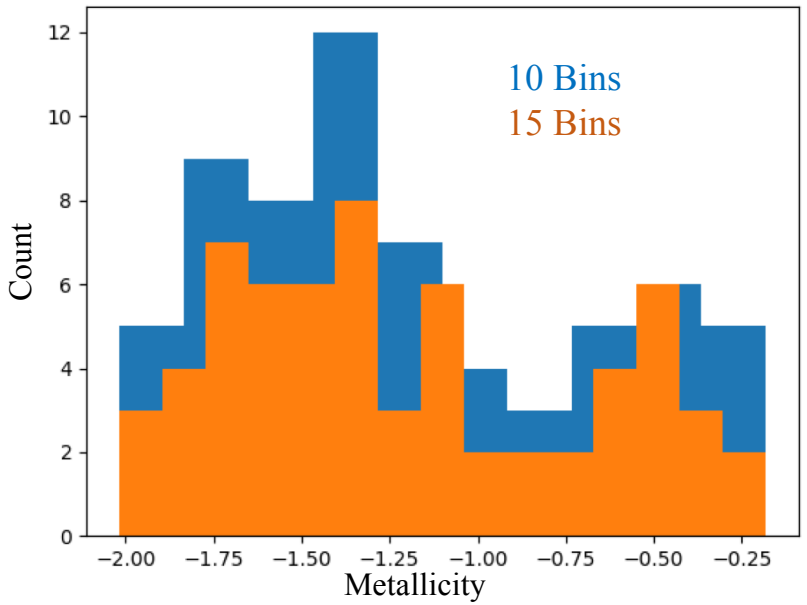
| | | | |
|---|---|---|---|
| Omnibus: | 0.232 | Durbin-Watson: | 1.697 |
| Prob(Omnibus): | 0.891 | Jarque-Bera (JB): | 0.002 |
| Skew: | 0.001 | Prob(JB): | 0.999 |
| Kurtosis: | 3.031 | Cond. No. | 38.8 |

## 3D Scatter with Model




- Model predicts: Low metallicity, Younger = Higher energy, High metallicity, Older = Lower energy
- No High metallicity, Old clusters in data
- Appears to be two metallicity populations: Metal Poor and Metal Rich

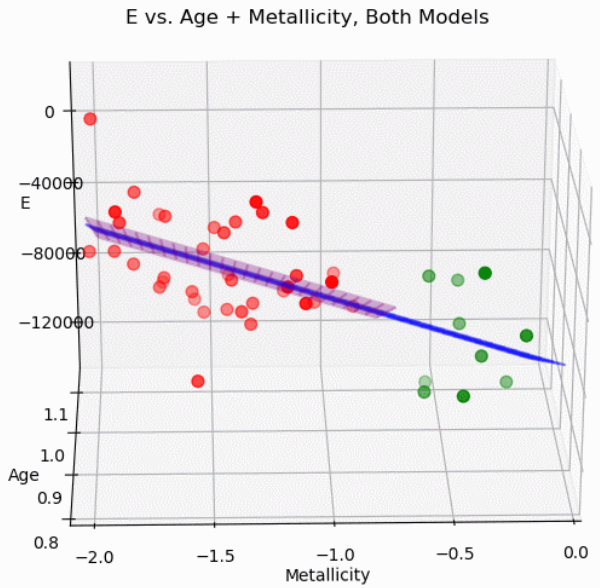
## Metallicity Histogram




## 3D Scatter with both Models

Data Points:
Metal Poor
Metal Rich

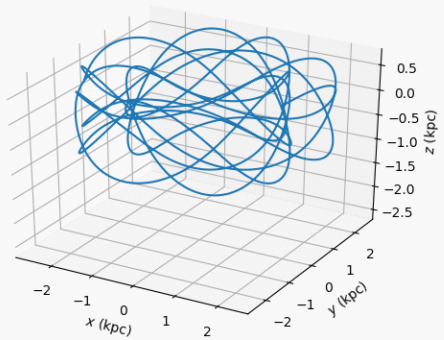
Plane Models:
Full Model
Metal Poor Model

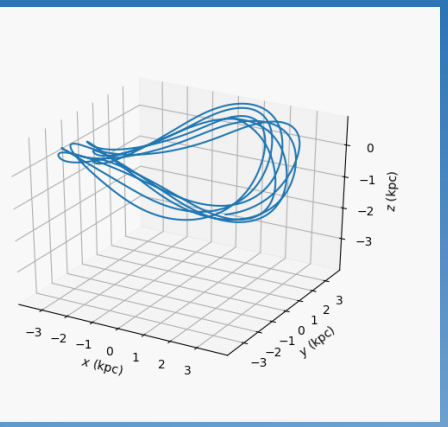



## Metal Poor Only Model

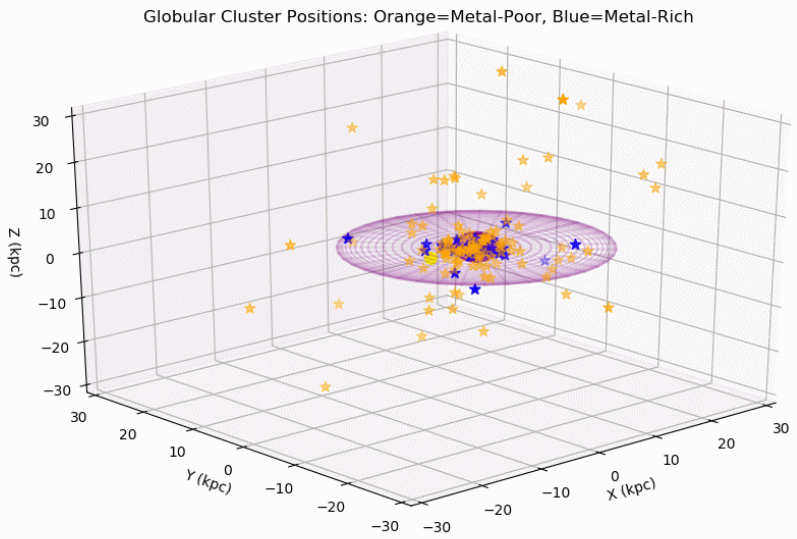
| | coef | std err | t | P>\|t\| | [0.025 | 0.975] |
|---|---|---|---|---|---|---|
| Intercept | 1.218e+05 | 5.34e+04 | 2.283 | 0.029 | 1.34e+04 | 2.3e+05 |
| MetalZW | -3.807e+04 | 1.39e+04 | -2.735 | 0.010 | -6.64e+04 | -9785.580 |
| AgeZW | -2.313e+05 | 5.61e+04 | -4.122 | 0.000 | -3.45e+05 | -1.17e+05 |

## Metal Rich Orbits



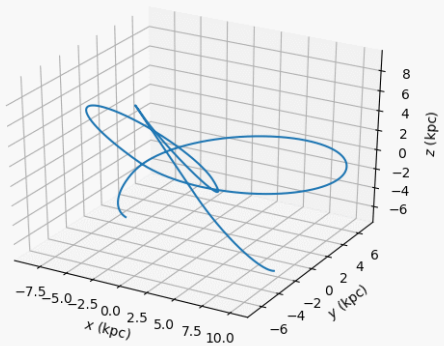



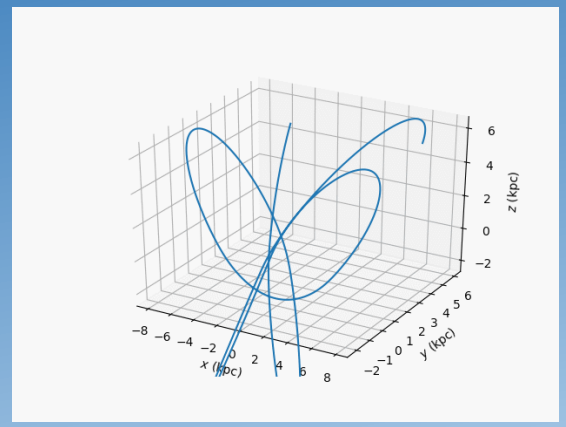

- Metal Rich: Flatter, More Regular, Close to Core
- Metal Poor: Randomly Oriented, Less Regular, Further from Core




Data Points: Metal Rich, Metal Poor

## Metal Poor Orbits



# Conclusions

- Strong correlation between a GC's Age, Metallicity, and Energy:

  Young, Low metallicity = Higher energy; Older, High Metallicity = Lower energy

- There appear to be two subgroups of GC's: Metal Rich and Metal Poor
- Metal Rich are Young with Low energy and Flat, Tight orbits
- Metal Poor tend to a gradient described in both models: Younger have Higher energy, Older have Lower energy