THE OPEN CLUSTER M67 AS A FUNDAMENTAL STANDARD OF REFERENCE FOR STELLAR PROPERTIES

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ABSTRACT. With the possible exception of the Hyades, M67 is the best-studied star cluster. Accurate photoelectric photometry exists well down onto the main sequence and proper motion studies have isolated cluster stars from the field. From photometry and spectroscopy, its composition is determined to be almost exactly the same as the Sun, with an age about one-half billion years less. This similarity to the Sun permits an accurate determination of distance to M67 independently of other distance measurements. Using the Sun as a reference, the distance modulus of M67 is found to be 9.48 mag. An extensive analysis of possible sources of error leads to an uncertainty (standard error) of ± 0.15 mag., with the chief sources of error being the color index of the Sun, the composition of the cluster, and its age. The M67 distance uncertainty compares favorably with Hanson's (1975) Hyades modulus of 3.29 ± 0.08.

1. INTRODUCTION

Because of the close resemblance in age and composition between M67 stars and the Sun, the M67 distance modulus can be found using the Sun as a reference, with no dependence on trigonometric distances. Its accuracy depends on the extent to which M67 and the Sun are matched and on the accuracy of the photometry of both M67 and the Sun.

A key reason why some confidence can be placed on the distance determination of M67 lies in the fact that there have been a number of photometric studies of the cluster (see Janes and Smith, 1984, for a review of the photometry). Schild (1983) and Janes and Smith (1984) find agreement among the various systems to better than 0.01 mag. (mean deviation) in both the V and B–V indices. For this analysis, Racine's (1971) photometry is used, since it includes much of the earlier photometry.

The absolute visual magnitude of the Sun is $M_V = 4.83$ (Allen, 1973) and its color index, B–V = 0.65 (Vandenberg and Bridges, 1984). A mean line through the M67 main sequence between $m_V = 13.5$ and $m_V = 15.5$ yields $m_V = 14.53 \pm 0.05$ at the solar B–V. After correcting for a

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reddening of E(B-V) = 0.056 (Janes and Smith, 1984) and assuming $A_V = 3.2E(B-V)$, then the distance modulus of M67 is $(m-M)_0 = 9.52$. Janes and Demarque (1983) found M67 to be about 4.1 billion years old. Assuming an age of 4.6 billion years for the Sun (Ostic, et al, 1963), an evolutionary correction of 0.04 mag. is required, bringing the M67 distance modulus to 9.48.

2. ANALYSIS

How good is this value? The estimated error derives mainly from the uncertainty in the color index of the Sun, the composition of M67 and the age of M67. The consequences of these and other sources of error are summarized in Table I and in the following paragraphs.

Table I - Sources of Error in M67 Distance Modulus

Parameter	Value	Adopted Error	Contributions to Error in (m-M)
$(B-V)_0$	0.65 mag	±0.015	±0.075
M67 composition	solar	±20%	±0.075
M67 Age	4×10^9 yrs	$\pm 10^9$	±0.08
Solar Age	4.6×10^9 yrs	$\pm 2 \times 10^8$	±0.02
M_{V0}	4.83 mag	±0.03	±0.03
E(B-V)	0.056 mag	±0.005	±0.025
m.s. at $(B-V)_0$	14.53 mag	±0.05	±0.05
$R = A_V/E(B-V)$	3.2	±0.2	±0.01
$(m-M)_{M67}$	9.48	---	±0.15

The B-V color index of the Sun has been disputed for some time; based on an extensive review, Vandenberg and Bridges (1984) derived a value of 0.65. Since the value is almost certainly greater than 0.63 and less than 0.67, an uncertainty of ±0.015 is adopted here. The slope of the M67 main sequence is about 5 so an uncertainty of ±0.015 in B-V translates into ±0.075 in V.

Based on the discussion in Janes and Smith (1984) and a survey of recent literature, M67 must have a metallicity very close to that of the Sun and a little less than the Hyades metallicity. The uncertainty in this value is of the order of 20% (0.08 dex). From the Vandenberg and Bridges (1984) theoretical main sequences, the effect of metallicity on M_{Bol} at the solar T_{eff} is 0.91 mag/dex.

In the context of current models (Janes and Demarque, 1983), M67 has an age of 4 billion years, but although the internal error is rather small, residual uncertainties in the models suggest a possible age uncertainty as large as one billion years. An analysis of the Vandenberg (1983) isochrones shows that at the solar effective temperature, the main sequence increases in luminosity by 0.08 mag/10^9

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years in the period between 3 and 5 billion years of age.

Other factors necessary to consider are the uncertainties in the solar luminosity and age, the interstellar reddening to M67, the finite width of the (observed) M67 main sequence and the uncertainty in the ratio of total-to-selective absorption, R. The adopted uncertainties for these parameters are shown in Table I.

The helium abundance is an unknown quantity. Vandenberg and Bridges (1984) find that it does not strongly affect the luminosity of the main sequence at a given color, and it is likely, in view of the age and metallicity of the cluster, to be close to the solar value. Consequently, the helium question is ignored.

The various sources of error discussed in the preceeding paragraphs are essentially independent of one another, so a straightforward calculation of the r.m.s. error in the M67 distance modulus gives ±0.15 mag. This compares favorably with Hanson's (1975) Hyades modulus of 3.29 ± 0.08.

3. SUMMARY

The apparent magnitude of the Hyades main sequence at the solar B-V is m_V = 8.15. If the age of the Hyades is about 0.8 billion years, an evolutionary correction of -0.20 is necessary to compare the Hyades to the M67. The Hyades metallicity [Fe/H] = 0.15, so an additional correction of +0.14 is required. These figures imply a distance modulus of M67 that is larger than that of the Hyades by 6.26; or using the M67 value of (m-M) = 9.48, a value for the Hyades of (m-M) = 3.22 results. For comparison, Hanson (1975) found (m-M) = 3.29 for the Hyades. While the possibility of compensating errors exists, the self-consistent set of results presented here strongly suggest that the stellar evolution models of Vandenberg (1983) are reliable and furthermore that M67 is close to the Sun in composition and 4 billion years old.

4. REFERENCES

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DISCUSSION

POPPER: What kind of analysis leads to your confidence that the chemical abundance of M 67 is close to that of the Sun? Is there an analysis of high-dispersion spectra of main sequence stars or only of the brighter giants?

JANES: Most of the work that has been done is low-resolution work (photometry and spectroscopy). There are, however, a few high-resolution studies, both of giants and the upper main sequence.

CAYREL: I agree with Dr. Janes that the [Fe/H] value of M 67 is equal to that of the Sun. Very recently one of my students, Dominique Proust, analyzed detailed spectra of two yellow giants of M 67 and found that their Fe-abundance was equal to that of the Sun.

GARRISON: Some years ago I did MK classification of the main sequence of NGC 752. What I found was that the dwarfs were identical to Hyades dwarfs of the same spectral type. This was confirmed by Crawford using Strömgren photometry. Most previous photometry and high-dispersion analyses had been done on giants, hinting at a possible difference in composition between giants and dwarfs. Do you see this effect for M 67?

JANES: In my survey of the literature relating to the chemical composition of M 67 I included studies both of giants and dwarfs in the cluster, as well as studies based on photometry and spectroscopy at various spectral resolutions. For the most part, they are in good agreement with one another. Although I did not check on NGC 752 in this survey, I seem to recall an impression that it might be a little metal-rich. Finally, there is no confirmation of the Spinrad and Taylor super-metal-rich designation of M 67.

GARRISON: Morgan classified M 67 stars from the same spectra used by Spinrad and Taylor and found them to be normal, in contrast to the results of Spinrad and Taylor who found them metal-rich. This is published in the Astrophys. J. about 12-15 years ago. Spinrad's results were due to use, or, misuse, of out-of-focus standards with respect to the cluster stars.