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THE ASTROMETRIC BINARY μ CAS: PHOTOGRAPHICALLY ALMOST RESOLVED, AND ITS IMPLICATIONS ON THE PRIMORDIAL HELIUM ABUNDANCE

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ABSTRACT

The Population II sub-dwarf star μ Cas was photographed on two occasions with two different telescopes, yielding elongated images from which the separation and magnitude of the unseen component can be derived. Photometry in the R-band yields a separation of $\sim 1.15 \pm 0.05$ arcsec and $\Delta m_R > 4$. The data are consistent with the predicted $\Delta m_v \approx 6$ and d = 1."14 by Dennis (1965) and remove the uncomforably large mass of $1.5 M_\odot$ derived from scanner observations of Hegyi and Curott (1970). The data also explains some reported negative observations such as speckle interferometry at $\lambda 5000$ to a limiting magnitude of $m_v = +9$ (Gezari, Labeyrie and Stachnik, 1972).

From models calculated by Dennis (1965) for $\Delta m_v \approx 6$ and d = 1."14, a mass of $0.75 M_\odot$ and helium abundance Y of 29 percent and 37 percent are derived for Z = .005 and Z = .015, respectively.

I. INTRODUCTION

One of the major points of interest in cosmology in recent years has been the problem of determining the primordial helium abundance since it may be a clue to distinguish between rival cosmological theories. A model based on Einstein's theory of general relativity predicts a helium abundance of 28 percent by mass, while the Brans-Dicke scalar-tensor model predicts a negligible amount (Peebles 1966; Wagoner, Fowler and Hoyle 1967; Dicke 1968). Direct determination of the helium abundance from emission line intensity ratios is not possible since the oldest objects are too cool to excite the helium lines. There is, however, another way to determine the abundance by the theory of stellar interiors and homology relations. Dennis (1965) has shown that if the mass and luminosity of a Population II star were accurately known, one could derive its helium abundance. He further pointed out that there seems to be only one known stellar system to which this test might be applied: the sub-dwarf Population

II astrometric binary μ Cas, ($01^h1.6^m$, $+54^\circ 26'$, 1900). Its spectrum is G5VI (Roman, 1955), $m_v = 5.20$. If the separation and magnitude of the unseen component could be determined, a significant step towards the solution of the problem of the primordial helium abundance would result. This paper describes photographic observations of μ Cas taken in 1964 and 1965 which almost resolved the components and permit an estimate of their separation, magnitudes and consequently an inferred helium abundance based on the models calculated by Dennis (1965).

II. BACKGROUND

The binary nature of μ Cas was discovered from Allegheny parallax plates by Wagman (1961) who calculated a provisional orbit with a period of 23 years. A more detailed study based on Sproul and Allegheny material was published by Lippincott and Wyckoff (1964).

They calculated an orbit with a period of 18.5 years and a maximum separation of the order of 1 arcsec to occur in 1964. While separations of the order of 1 arcsec are not difficult to observe if the components are of nearly equal magnitude, the problem with μ Cas is a large difference in magnitude, Δm, which has prevented direct observations of the faint component, either photographically or visually. The only visual sighting of the faint component was an announcement by Wehinger and Wyckoff (1966) who used the 84-inch Kitt Peak reflector, but this claim was later withdrawn.

Arp (1971), at the request of the author, kindly provided a print of μ Cas taken with the 200-inch Palomar reflector, but the exposure was too long. A shorter exposure or masked-down aperture would have been required to prevent the bright component from drowning out the image of the faint companion. The time for this observation was near minimum separation, thus further aggravating the difficulty.

Hegyi and Curott (1970) used a clever scanner technique to sample the binary image at fast rates so as to eliminate seeing effects. They were able to derive a separation of 1.09 arcsec and a $\Delta m \leq 3$ without actually seeing the companion, and from this data they calculated the mass and helium abundance. The uncomfortably large mass of $1.5M_{\odot}$ and deduced zero-abundance of helium has been questioned by Faulkner (1971) in a detailed critique.

Gezari, Labeyrie and Stachnik (1972) used speckle interferometry at λ_{eff} 5000 on the 200-inch reflector but could not detect the companion. Their limiting magnitude was $+9m_v$. It will be shown later that at this wavelength the companion is about 9^m or fainter, but might just have been detectable if λ_{eff} had been 6500Å.

Plates exposed for the regular Allegheny parallax program employ a rotating sector to attenuate the brightness of the $5.2m_v$ primary so that its image matches comparison stars of $m \cong 10$. Consequently, the image of the secondary is attenuated by a proportional amount and therefore, falls below the detection threshold. Furthermore, since the secondary is believed to be a late type star, ordinary blue sensitive parallax plates would not be the best way to record it.

III. OBSERVATIONS

With a maximum separation of the components of μ Cas to occur in the 1964-65 observing season, that period was concentrated on to attempt resolving the pair photographically. It was decided to observe in the red region of the spectrum to diminish the large expected Δm and favor the faint star. The Thaw refractor is normally not used in the red region of the spectrum but extensive tests and observations of nebulae in H-alpha confirmed that excellent results could be obtained, provided that the wavelength region is restricted to a band of about 400Å using a Corning 2403 glass filter and Eastman Kodak 103a-E emulsions. This combination requires a change in the focal setting of about +46 mm and also changes the plate scale slightly, from a nominal 14.6 arcsec/mm to 14.553.

Several dozen red exposures of μ Cas were taken in 1964 with the 76 cm refractor, as well as a few ordinary blue ones. The red images of μ Cas are elongated or egg-shaped, while the blue ones are round. The star θ Cas (m_v = 4.2, A7V, about 0.5 degree from μ Cas) was photographed on the same plate with μ Cas on a few occasions as a control and its image was round on red and blue plates. Exposure times were quite critical since too short an exposure would not record the elongation, while too long an exposure caused swelling of the bright component which swamped the faint one. The best results were obtained on Nov. 27-28, 1964, as shown in Fig. 1a.

In the following year, 1965, as guest investigator at the Harvard 155 cm reflector, that instrument was used with the same filter-plate combination and the results are shown in Fig. 1b. Exposures were adjusted so that images from the prime focus f/5.1, 155 cm reflector data were equivalent to those of the f/18.5, 76 cm refractor.

Two Allegheny blue plates, taken in 1964 and 1965, without filter on 103a-O, show a faint star about 10 arcsec west of μ Cas. This star, shown in Fig. 2, has not been recorded before since it is hidden by the rotating sector used for the parallax plates. The star is of approximately 11^m and the attenuated image is much below the short parallax exposures. It is probably a background star not physically associated with the system μ Cas, but this assumption should be verified since it would affect the masses of the components.

Precautions were taken to eliminate the possibility that the elongated images might have been due to instrumental effects. A light weight shutter was installed to prevent the telescope from being jarred in declination when the normally employed heavy duty curtain type shutter was used.

Table 1 gives the relevant data for the observations.

Table 1

Date	Instrument	Exposure, sec.	Emulsion and Filter
1964 Nov. 27-28	76cm refractor	30,60,120	103a-E, Corning 2403
1965 Sept. 29-30	155cm reflector	4, 8, 16	103a-E, Corning 2403
1965 Oct. 13-14	76cm refractor	90	103a-O, No filter

IV. REDUCTION

The object of this investigation was to determine the separation of the two components of μ Cas, establish the relative position angle and determine the magnitude of the fainter star. Although the images are not completely resolved, the data obtained with two different instruments permit a fairly accurate measurement of the separation and position angle and at least an upper limit for the magnitude of the secondary. A separation of 1.″15 ± 0.″05 was measured for the 1964 data by means of a Gaertner measuring machine. The position angle was $194^{\circ} \pm 0\overset{\circ}{.}5$ in 1964 and $201^{\circ} \pm 0\overset{\circ}{.}5$ in 1965.

Magnitude estimates for the faint companion required an intermediate calibration step based on image diameter sizes as a function of exposure time for the red region of the spectrum. The brighter satellites of Saturn were used as reference points since homogeneous sets of graded exposures were available for them in the linear portion of the photographic response. Five points were available for Titan ranging from 5 seconds to 180 seconds. Two measurements each for Rhea, Tethys and Dione and 3 points for μ Cas were plotted in Fig. 3, resulting in a set of parallel lines. From the shortest exposures of μ Cas the image diameter of the faint component B was measured to have been 1/3 the diameter of the bright component A. Therefore, a dashed line was drawn parallel to the set of lines through the point labelled 1/3 μ Cas A. This line is seen to intercept the vertical magnitude scale on the right side near the value of 9. This somewhat roundabout photometry is clearly not intended to give the precise or final magnitude value for μ Cas B, but it does indicate that the difference in magnitude, Δm, is of the order of 4 in the red and probably larger in the visible, based on the Johnson-band Photometry, given by Dennis (1965). Atmospheric extinction was not taken into account since μ Cas was near the zenith at the time of the observations and any extinction corrections would be negligible compared to the other uncertainties involved in the magnitude estimates of μ Cas B.

V. CONCLUSIONS

Faulkner (1971) has raised several doubts about the results derived from the observations of Hegyi and Curott

(1970). The present work avoids some (though not all) of these doubts. Specifically, Faulkner questions the following points:

a. The data of Hegyi and Curott were obtained 4-1/2 years after the last data for the orbit determination, at a time when the separation was rapidly diminishing. The present work is based on data taken in 1964 and 1965, at maximum separation, if one accepts the 18.5 year orbit of Lippincott and Wyckoff (1964). Some uncertainties about the period and epoch of periastron passage still exist.

b. Faulkner applied a correction to the orbital elements which reduces the calculated mass of μ Cas A slightly, but still results in an uncomfortably large value of $1.37M_{\odot}$, as compared to a value of $1.54M_{\odot}$ derived by Hegyi and Curott. For either case, however, the implied helium abundance is near zero.

c. Some uneasiness expressed by Faulkner about the fact that the published results contained only a small subset of data is probably unfounded since the material is discussed in considerable detail in the dissertation by Hegyi (1968, Princeton, unpublished). Three other items not mentioned in the paper are given in the dissertation and are of interest: (i) Their approach to the measurements of the separation was essentially one of a statistical nature, with elongation due to the secondary occurring on 42 runs out of 62, though the total number of image samplings was about 20,000. (ii) The position angle for the year of observation, 1967, is given as 215°. This is consistent with the photographic results of the present work for 1964 and 1965, i.e. the value of the position angle increases as a function of time. Unfortunately, however, this is contradictory to the photocentric orbit published by Lippincott and Wyckoff (1964). An accidentally inverted sign somewhere in the orbit calculations could account for the reversal. An alternate, perhaps less likely, explanation could be found if the fainter component of μ Cas is the more massive one, but the possibility of it being a white dwarf seems remote. (iii) Finally, a statement is made that for a star fainter than $m_v = 7$ the scanner trigger circuit approaches noise limitations. From Fig.3 of the present work it appears that μ Cas B is almost certainly fainter than 7^m.

To arrive at an estimate of the helium abundance for the present photographic work we will adopt a red magnitude difference of approximately 5, which, according to Table III of Dennis' (1965), corresponds to a visual

Δm of about 6. Dennis used metal abundances Z calculated by Catchpole, Pagel and Powell (1967) in his Table II which gives 5 sets of expected characteristics of the system μ Cas. For the adopted values of d = 1".15 ± 0".05 and Δm_V = 6, the present work corresponds very nearly to Dennis' second set of calculations reproduced here:

m_A/m_B	d	m_A	Z = .005	Z = .015	Δm_V
4.2	1".14	0.75	Y = 0.29	Y = 0.37	6.0

In summary then it appears that for the observed parameters d and Δm for μ Cas, a helium abundance of 29 percent and 37 percent results for a given Z = .005 and Z = .015, respectively, and a mass $m_A = 0.75 M_\odot$.

These conclusions are obviously of a provisional nature pending further observations and refinements in the orbit. The next few years should give ample opportunity to measure the separation as it again approaches maximum

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FIGURE CAPTIONS

Fig. 1 - μ Casseiopeia

a. 30, 60, 120 sec exposures
Allegheny 76 cm refractor
Nov. 27-28, 1964
103a-E plus Corning 2403 filter

b. 4, 8, 16 sec exposures
Harvard 155 cm reflector
Sept. 29-30, 1965
103a-E plus Corning 2403 filter

Fig. 2 - A faint star is seen about 10arcsec west of the overexposed image of μ Cas on this 90 second exposure. Oct. 13-14, 1965, 76 cm refractor, 103a-O without filter.

Fig. 3 - Red magnitude estimate of μ Cas B from photographic photometry of 4 satellites of Saturn and μ Cas A.

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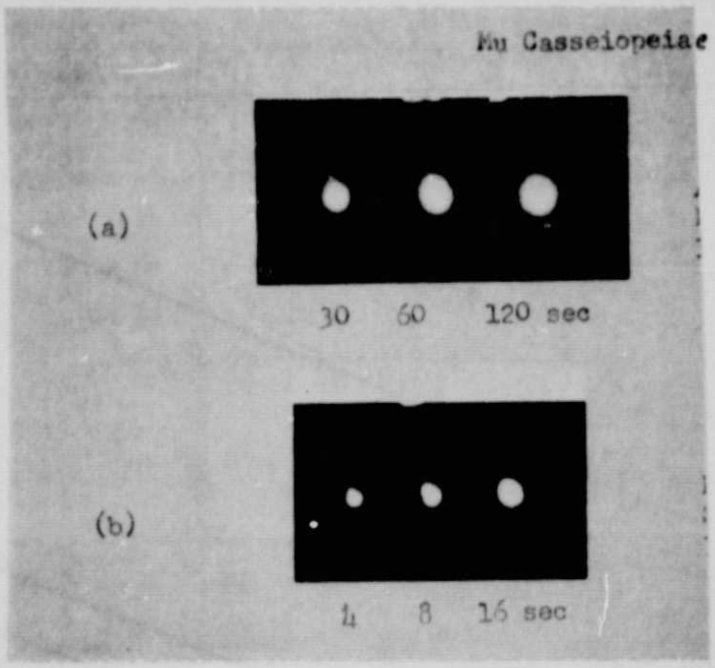


Fig 1.

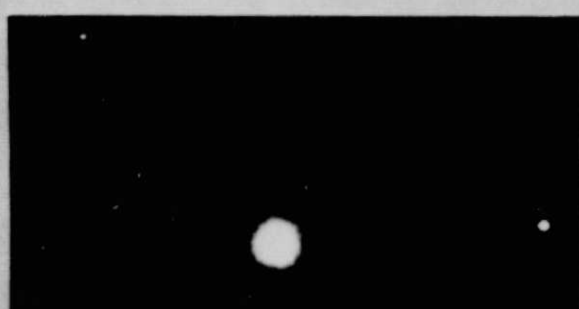
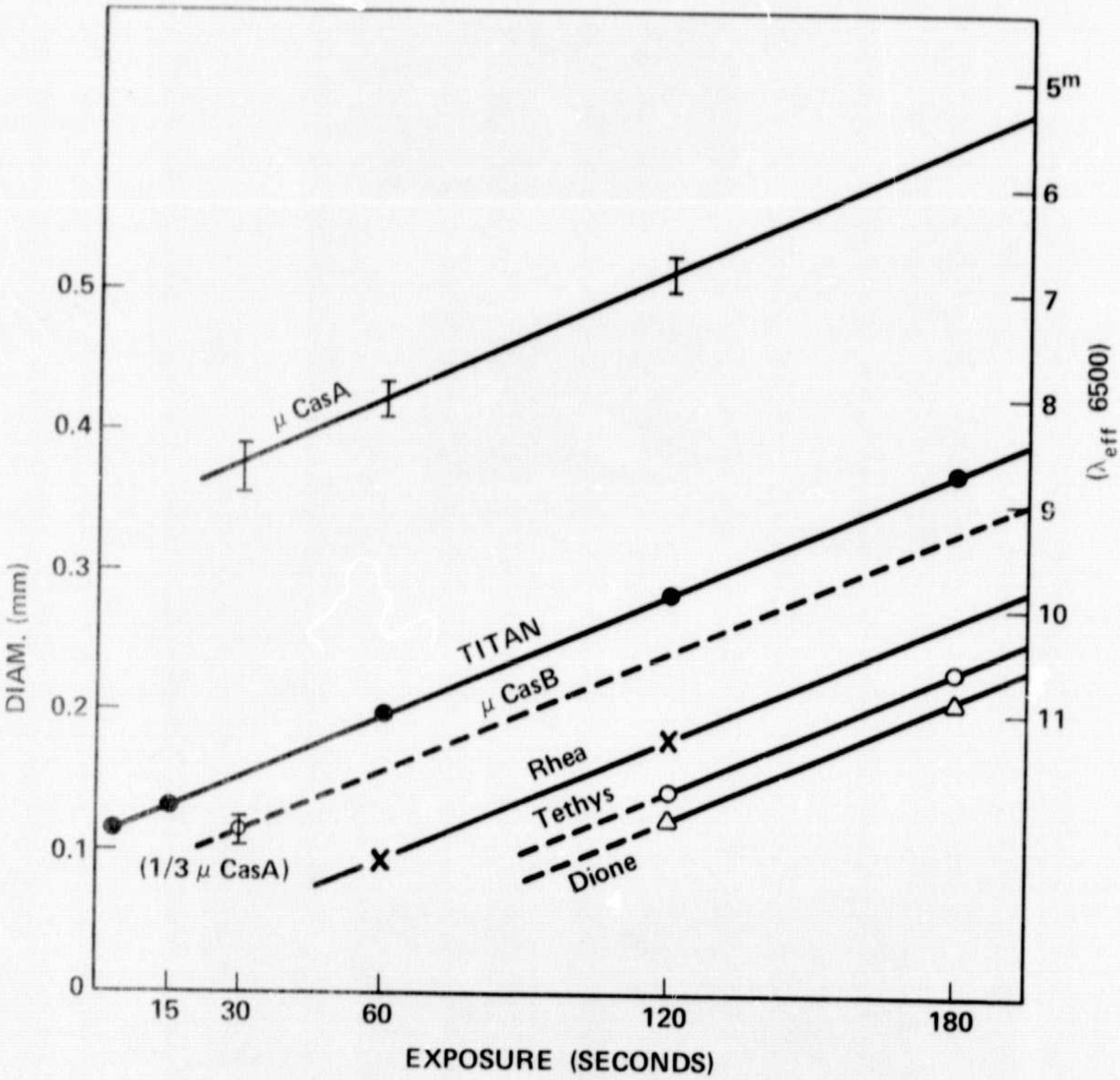


Fig.2

A faint star is seen about 10 arc-sec west of the overexposed image of μ Cas on this 90 sec exposure. Oct.13/14, 1965, 76 cm refractor, 103a-O without filter.



0.5
0.4
0.3
0.2
0.1
0
DIAM. (mm)
15
30
60
120
180
EXPOSURE (SECONDS)
5m
6
7
8
9
10
11
(λeff 6500)
μ CasA
TITAN
μ CasB
Rhea
Tethys
Dione
(1/3 μ CasA)

Fig 3