UNRAVELING THE MACH● MYSTERY

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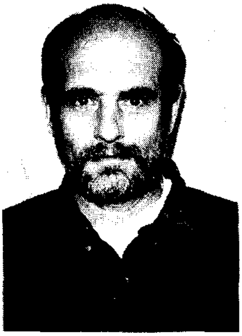

Abstract

The number of Machos (Massive Compact Objects) being detected toward the Large Magellanic Cloud (LMC) is 5 times too low for a standard dark halo, but based on star counts using the *Hubble Space Telescope*, 4 times too high to be due to known stars. The event rate toward the galactic bulge is a factor ~ 2 too high according to the standard model of the galaxy. This means that there is more matter in the luminous components (disk+bulge) than previously thought, and so less need for a dark halo. The events seen toward the LMC may represent all the halo that is needed. To determine the nature of the Machos, new methods and new experiments are needed. I describe satellite and ground-based observations that can resolve the issue.

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1. Introduction

The MACHO collaboration[1,2] and the EROS collaboration[3] have reported a total of 5 candidate microlensing events toward the Large Magellanic Cloud (LMC). From the time scales, the mass of the objects is $\sim 0.1\, M_\odot$ and the optical depth (the probability that any given star is lensed at any give time) is $\tau \sim 10^{-7}$. This value of τ is ~ 5 times smaller than would be expected from a standard dark halo of Machos (Massive Compact Objects). The MACHO collaboration[4,5] and the OGLE collaboration[6] have reported a total of 56 candidate microlensing events toward the galactic bulge, corresponding to $\tau \sim 3 \times 10^{-6}$. This is a factor ~ 2 more than expected on the basis of standard models of stars in the Milky Way bulge and disk. These observations, initiated after the suggestions of Paczyński[7,8] and Griest et al.,[9] naturally raise the question: what are the Machos?

2. Contributions of Stars To Microlensing

Before concluding that the events observed toward the LMC are a new (heretofore unrecognized) type of object, it is important to examine the possibility that the events are due to previously known objects. Such objects could include stars in the Milky Way disk, in the Milky Way spheroid, or in the disk of the LMC. Indeed, Sahu[10] has recently argued that the last could account for all the events.

How much do known stars contribute to microlensing? Strong limits can be placed on the contribution of spheroid stars by the failure to find any red $(V - I > 3)$ stars in an ultra-deep $(I < 25.2)$ image taken by the Wide Field Camera (WFC2) on the repaired *Hubble Space Telescope (HST)*. We find that spheroid stars contribute $\tau < 7 \times 10^{-9}$.[11]

Subsequently, we analyzed a total of 22 WFC2 images to a mean limiting mag $\bar{I} < 23.8$ and combined these results with ground-based photometry of stars in 162 images on the Planetary Camera of the pre-repair *HST* to make a new measurement of the faint end of the disk luminosity function (LF).[12,13] We restricted attention to 255 M stars $(8 < M_V < 18.5)$ above the hydrogen burning limit and within 3200 pc of the galactic plane. We find that the LF cuts of rather sharply at the faint end $(M_V > 12)$ in good agreement with a previous ground-based photometric study[14] but in strong apparent contradiction to the nearly flat LF found from local parallax stars.[15] The latter study has formed the basis for most recent estimates of the stellar density. However, recent further observations and reanalysis of the parallax stars shows that they are in much closer agreement with the *HST* LF than previously believed.[16] We also derived a vertical distribution from our data which we parameterized with two 2-component models. Both models have a (kinematically) hot exponential component. The first model has a cold exponential component and the second has a cold sech^2 component. We find that estimates of the total optical depth to microlensing are insensitive to the choice of model and also insensitive to changes in the model parameters (within the errors). The basic reason for this is that our data extend to many scale heights. We extend our results on M stars to earlier type stars that are much more easily studied from the ground and also to white dwarfs and giants and find a total optical depth to disk stars $\tau = 8 \times 10^{-9}$.

Finally, I have proven an analytic result that the optical depth due to a self-gravitating disk of stars is given by $\tau < 2(v_z/c^2)\sec^2 i$, where v_z is the vertical dispersion of the stars and i is angle of inclination of the disk.[17] Applying this to the LMC, with $v_z \sim 20\,\mathrm{km\,s}^{-1}$ and $i \sim 27°$, I find $\tau < 10^{-8}$. Combining these results, I find $\tau < 2.5 \times 10^{-8}$, that is about 4 times smaller than the observed value.

It remains possible that with so few events, we are the victims of an extreme statistical fluctuation. Or that some of the events will turn out to be variable stars. For the present, however, we should consider the possibility that we are seeing a new population. This population is certainly too small to be a full "standard" dark halo, but could it be a full "non-standard" dark halo. That is, has the need for a dark halo been overestimated?

3. Excess Bulge Events

According to the original estimates of Paczyński[8] and Griest et al.[9], the optical depth toward the bulge due to disk stars is $\sim 5 \times 10^{-7}$ while self-lensing due to bulge stars is negligible. However, Kiraga & Paczyński[18] pointed out that for an axisymmetric bulge, self-lensing is at least as important as disk lensing. Furthermore, they noted, if the bulge were elongated in our direction, then the optical depth could be much higher. Arguments for such a triaxial bulge had been made previously based on stellar kinematics, infrared light and other non-lensing observations. Thus, it seemed that the high bulge $\tau \sim 3 \times 10^{-6}$ might be explainable from known stellar populations. Virial theorem estimates for a non-rotating[19] and rotating[20] triaxial bulge led to estimates for $\tau \sim 1.3$ and 1.7×10^{-6}, with corresponding bulge masses 1.8 and $2.6 \times 10^{10}\,M_\odot$. A more detailed model with intermediate rotation gave an intermediate result.[21]

These higher bulge optical depths still do not account fully for the observed lensing rate. But they do illustrate one important point: no matter how the higher bulge optical depth is explained, it requires more mass in the luminous components of the galaxy (disk+bulge) than was previously believe. Hence this leaves a smaller need for a dark halo. Thus, these bulge events raise possibility that the entire halo is composed of Machos.

4. Resolving the Macho Mystery

Why is there a Macho mystery? Basically because we have inadequate information on the individual Macho events. The fit to a Macho light curve has just 3 parameters. The magnification is given by

$$A(x) = \frac{x^2+2}{x\sqrt{x^2+4}}; \quad x(t) = \sqrt{\omega^2(t-t_0)^2+\beta^2}, \tag{4.1}$$

where t_0 is the time of maximum magnification, β is the impact parameter in units of the Einstein radius, r_e, and ω^{-1} is the characteristic time scale of the event. Hence detection of an event gives exactly three pieces of information: ω, β, and t_0. Unfortunately, two of these pieces of information are completely useless: the time and impact parameter are just random variables with no physical significance. The one meaningful parameter is a complicated combination of the three parameters one would like to know, M, $D_{\rm OL}$, and v:

$$\omega = \frac{v}{r_e}; \quad r_e^2 = \frac{GMD_{\rm OL}D_{\rm LS}}{c^2 D_{\rm OS}}, \tag{4.2}$$

where v is transverse speed of the Macho relative to the Earth-source line of sight, M is the Macho mass, and $D_{\rm OL}$, $D_{\rm LS}$, and $D_{\rm OS}$ are the distances between the observer, source, and lens.

How then can the other two parameters be recovered? If the event were viewed from a satellite in solar orbit, it would look very different. For typical parameters, the size of the Einstein ring is $r_e \sim 1\,\rm AU$. Hence, the event as observed from 1 AU away would have a different impact parameter and different time of maximum magnification, β' and t_0'.[22,23,24,25] By comparing t_0 with t_0' and β with β' one can measure the separation of the Earth and the satellite in units of the Einstein ring. Since the physical size of the Earth-satellite separation is known, one measures the physical size of the Einstein ring. The 'useless' parameters t_0 and β now yield important information. "Any man can make use of the useful, but it takes a wise man to make use of the useless" (Lao Tzu).

More careful analysis shows that the actual parameter measured in this way is not r_e, but $\tilde{r}_e = (D_{\rm OS}/D_{\rm LS})r_e$. In fact, even $\tilde{r}_e$ is not quite so easy to measure because from the light curves alone one only measures the magnitudes of the impact parameters β and β': One does not measure their signs, i.e. which side of the Einstein ring the source passed relative to the Macho. If the source passed on the same or opposite sides as seen from the Earth and satellite, then $\tilde{r}_e = r/\sqrt{\omega^2(t_0-t_0')^2+(\beta\mp\beta')^2}$. This ambiguity can actually be resolved by measuring a slight difference in the time scale $\omega'-\omega$ as seen from the Earth and satellite.[25)]

The projected speed $\tilde{v} = \omega \tilde{r}_e$ would give us an excellent idea of what the Machos seen toward the LMC are. If they are disk objects, they have speeds $v \sim 50\,\mathrm{km\,s^{-1}}$ and distances $D_{\mathrm{OL}} \lesssim 1\,\mathrm{kpc}$, so $\tilde{v} \sim 50\,\mathrm{km\,s^{-1}}$. For thick disk $v \sim 100\,\mathrm{km\,s^{-1}}$, $D_{\mathrm{OL}} \lesssim 3\,\mathrm{kpc}$, so $\tilde{v} \sim 100\,\mathrm{km\,s^{-1}}$. For galactic halo $v \sim 220\mathrm{km\,s^{-1}}$, $D_{\mathrm{OL}} \lesssim 10\mathrm{kpc}$, and $\tilde{v} \sim 270\mathrm{km\,s^{-1}}$. For LMC halo $v \sim 80\,\mathrm{km\,s^{-1}}$, $D_{\mathrm{LS}} \lesssim 3\,\mathrm{kpc}$, and $\tilde{v} \sim 1300\,\mathrm{km\,s^{-1}}$. For LMC disk $v \sim 30\,\mathrm{km\,s^{-1}}$, $D_{\mathrm{LS}} \lesssim 0.5\,\mathrm{kpc}$, and $\tilde{v} \sim 3000\,\mathrm{km\,s^{-1}}$. These projected velocities are well separated. Hence, measurement of only a few events would give a very good indication of the nature of the objects.

Toward the bulge, satellite parallax measurements give important but still ambiguous information. For events due to objects in the galactic disk $D_{\mathrm{OL}} \lesssim 4\,\mathrm{kpc}$, the parallax measurement will give the distance and mass to within $\sim 50\%$.[26] But for lenses that are closer to the galactic center, the measurement will reduce the space of uncertainty from 2 to 1 dimension, but will not allow even approximate measurement of any single parameter.

Can anything be done to obtain additional information for the events seen toward the bulge? For events where the Macho actually transits the face of the star, the light curve deviates from the standard 3-parameter curve.[27,28)] In addition to ω, t_0, and β, the curve depends on the ratio of the angular size of the star to the angular size of the Einstein ring, θ_s/θ_*. Since the angular size of the star is known from its temperature (color), flux (apparent magnitude), and Stephan's Law, the measurement of this additional parameter gives $\theta_* = r_e/D_{\mathrm{OL}}$. This is often called a "proper motion" measurement because the proper motion $\mu = \omega\theta_*$. How often does it happen that a Macho transits the source? For the short events observed toward the bulge $\omega^{-1} \sim 10\,\mathrm{days}$. If the events are arising from bulge lenses (as they probably are), then $v \sim 200\,\mathrm{km\,s^{-1}}$, meaning that $r_e = \omega/v \sim 250\,R_\bullet$. The source stars in typical events are turnoff stars with radius $r_s \sim 2\,R_\odot$. Hence, the probability is rather low $\sim 1\%$. However, if the lensing search were reorganized to emphasize finding events with giant sources $M_I < 0.5$, then the mean radius of these sources would be $\langle r_s \rangle \sim 22\,R_\odot$.[29)] The probability would then increase to $\sim 9\%$. Moreover, with bright sources it would probably be possible to measure a proper motion with impact parameters as large as $\beta \sim 2\theta_s/\theta_*$. Hence the fraction of events with proper motions would be $\gtrsim 15\%$.

There are other ways to obtain proper motions as well. Witt showed that limb-darkening gives rise to color effects which can reveal the angular size of the Einstein ring.[30)] Simmons, Willis, & Newsam showed that limb polarization could be used to the same end,[31)] although it is not known if the number of stars with polarized limbs is sufficient to make this method worthwhile. The three effects mentioned so far fall off as $(\theta_s/\beta\theta_*)^2$ and so become hopeless at a few stellar radii. Maoz & Gould showed that when rotating sources are lensed, there is a shift in the spectral lines directly $\propto \theta_s/\beta\theta_*$. Hence, this method can potentially be used to many stellar radii. Unfortunately, most of the stars in the bulge are rotating only very slowly, but the method may be of use in the LMC.[32]

The above four methods all work better for small Einstein rings. MACHO has seen 4 long events in the bulge, $\omega^{-1} \sim 90\,$days. For these, one may estimate that the Einstein ring is of order mas. The chances that the impact parameter will be low enough to use one of these methods is negligible. However, for $\theta_* \gtrsim 1\,$mas, it is possible to make a measurement using lunar occultations of Machos.[33] At somewhat larger θ_* it may be possible to measure the apparent proper motion of the image.[34].

Finally, I should mention that when a binary[35] or a planetary system[35,36] is discovered, it is often possible to measure a proper motion. Such systems can be discovered by careful follow-up measurements similar to the ones needed to find the Macho transit events. In fact, such follow up of microlensing events is probably the best way to find planetary systems.

REFERENCES

1. Alcock, C., et al. 1993, Nature, 365, 621
2. Alcock, C., et al. 1995a, Phys. Rev. Lett., submitted
3. Aubourg, E., et al. 1993, Nature, 365, 623
4. Alcock, C., et al. 1995b, ApJ, 445, in press
5. Bennett, D. et al. 1995, preprint
6. Udalski, A., Szymański, J., Stanek, K. Z. Kaluzny, J., Kubiak, M., Mateo, M. Krzemiński, W., Paczynski, B. & Venkat, R. 1994, Acta Astron, 44, 165
7. Paczyński, B. 1986, ApJ, 308, L42
8. Paczyński, B. 1991, ApJ, 371, L63
9. Griest, K. et al. 1991, ApJ, 372, L79
10. Sahu, K. 1994, Nature, 370, 275
11. Bahcall, J. N., Flynn, C., Gould, A. & Kirhakos, S. 1994, ApJ, 435, L51
12. Gould, A., Bahcall, J. N. & Maoz, D. 1993, ApJS, 88, 53
13. Gould, A., Bahcall, J. N. & Flynn, C. 1995, in prepration
14. Stobie, R. S., Ishida, K., & Peacock, J. A. 1989, MNRAS, 238, 709
15. Wielen, R., Jahreiss, H., & Krüger, R. 1983, IAU Coll. 76: Nearby Stars and the Stellar Luminosity Function, A. G. D. Philip and A. R. Upgren eds., p 163
16. Reid, I. N., Hawley, S. L., & Gizis, J. E. 1995, ApJ, submitted
17. Gould, A. 1995a, ApJ, 441, 77
18. Kiraga, M. & Paczyński, B. 1994, ApJ, 430, 101
19. Han, C. & Gould, A. 1995, ApJ, 447, 000

20. Blum, R. 1995, ApJ Letters, in press
21. Zhao, H. S., Spergel, D. N., & Rich, R. M. 1995 ApJ, 440, L13
22. Refsdal, S. 1966, MNRAS, 134, 315
23. Gould, A. 1992, ApJ, 392, 442
24. Gould, A. 1994a, ApJ, 421, L75
25. Gould, A. 1994b, ApJ, 441, L21
26. Han, C. & Gould, A. 1995, ApJ, 447, 000
27. Gould, A. 1994c, ApJ, 421, L71
28. Nemiroff, R. J. & Wickramasinghe, W. A. D. T. ApJ, 424, L21
29. Gould, A. 1995b, ApJ Letters, in press
30. Witt, H. 1994, ApJ, in press
31. Simmons, J. F. L., Willis, J. P., & Newsam, A. M. 1995, A&A, 293, L46
32. Maoz, D. & Gould, A. 1994, ApJ, 425, L67
33. Naraynan, V., Han, C., & Gould, in prepartion
34. Hog, E., Novikov, I. D., & Polnarev, A. G. 1995, A&A, in press
35. Mao, S. & Paczyński, B. 1991, ApJ, 374, L37
36. Gould, A. & Loeb, A. 1992, ApJ, 396, 104