A LIMIT ON THE STELLAR POPULATION OF MASSIVE HALOS

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ABSTRACT

The measured rotational velocities of the edge-on spiral galaxy NGC 4565, coupled with several arguments supporting the spherical symmetry of halos, can be used to determine the space density of the halo mass. We show that if the halo mass surrounding NGC 4565 were contained in a population of M5 stars, the minimum expected surface brightness would exceed our measured halo surface brightness. These observations were made in the I Kron band with the annular scanning photometer.

I. Introduction

Over the last ten years evidence has been accumulating to substantiate the claim that spiral galaxies are surrounded by massive spherical halos.1),2) While the evidence to support the existence of massive halos is now quite compelling, little if any direct progress has been made towards the determination of the nature of the halo mass.

We shall show, based on optical observations made with the annular scanning photometer,19) that the halo of the spiral galaxy NGC 4565 is not primarily composed of M5 nor of more massive stars. The conclusion is based on the photometry of the faintest M5 subdwarf3) available with large parallax (>0.10 arc seconds). If fainter M5 subdwarfs are subsequently discovered then this conclusion will have to be modified.

Our derived limit on the allowed stellar population of halos is interesting because the mass of an M5 star, 0.14 $M_\odot$, is close to the lower mass limit for nuclear burning stars, ~.08 $M_\odot$.4) If the halo is composed of 0.14 $M_\odot$ nuclear burning stars, then there cannot be more than a factor of ~2 variation in mass in the nuclear burning portion of the initial mass function of the halo stars. Otherwise, the halo surface brightness would exceed our measured surface brightness. Such an initial mass function for the halo would be quite different from the presently observed mass function in the solar neighborhood.

II. Evidence for Halos

The strongest evidence for massive halos surrounding spiral galaxies comes from direct measurements of the rotation curves of spiral galaxies. Radio5),6),7) and optical8) observations of over 50 spiral galaxies show that the rotation curves of spiral galaxies are flat or increase slightly outward to the limits of detectability of the HI or optical disk. The fact that the rotation curves are symmetric about the optical center of the galaxies is a demonstration of the stability of the rotation and supports the equilibrium condition,

$$\frac{GM_r}{r^2} = \frac{v^2}{r} \quad , \qquad (1)$$

that gravity provides the centripetal force which keeps the observed particles in stable circular orbits. In Equation (1), M_r is the mass within galactic radius r, and v is the observed circular velocity. We have assumed that M_r is spherically symmetric and shall justify that assumption below.

Equation (1) should accurately describe the dynamics on a galactic scale. The left hand side of that Equation, Newton's Law of Gravitation, is at least as accurate as a part in 10^{10} on the scale of the solar system. On the very largest scale, $cH_0{}^{-1}$, the radius of the visible universe, Newton's Law of Gravitation also gives order of magnitude agreement. Therefore, it may be expected to work on the intermediate scale of galaxies as well. The right hand side of Equation (1) depends only on the geometrical properties of rotation. Solving Equation (1) for M_r, we find that

$$M_r = 1.45\times10^{12} \left(\frac{v}{250\ \text{km/s}}\right)^2 \left(\frac{r}{100\ \text{kpc}}\right) M_\odot \ . \qquad (2)$$

Many spiral rotation curves have been measured out to ~50 kpc and one optical rotation curve extends out to 120 kpc.8) To obtain information about the halo mass distribution beyond 50 kpc, binary galaxies have been used. The interpretation of the binary data is difficult because of selection effects introduced in the statistical reduction of the data. Nevertheless, the data are consistent with the halo hypothesis. The Turner9) and Peterson10) binary samples, which have median projected separations of 50 and 110 kpc, respectively, yield M/L ratios which are proportional to the median separations. This would be expected if the light were centrally concentrated, which it is, and if the halo mass increased linearly with galactic radius.

There is only one argument which appears to contradict the existence of large massive halos. White and Sharpe[11)] have numerical models of pairs of interacting galaxies showing that if the centers of the galaxies are closer than the radius containing half the mass, the galaxies merge in less than one orbital period. Based on the statistics of binary galaxies, they argue that binaries cannot be merging so rapidly, so that perhaps halos are not very large or not universally present. It is possible to construct a simple analytical model of a galaxy moving through the halo of a companion which gives similar results, so there is little reason to doubt the calculation. But one may question whether the initial conditions used for the models accurately describe the actual physical situation. It is the relative velocity of one galaxy streaming through the halo of the second which gives rise to dynamical friction. But it is possible that binary galaxies are formed with zero relative velocity between the core of one galaxy and the halo of the other, analagous to rigid body rotation. If binary galaxies formed with these initial conditions, then the White and Sharpe calculation would be expected to overestimate the merger rate. Of course, this possibility requires further support before it may be said to offer a solution to the apparent contradiction with the universality of large halos. In summary, we believe that, taken together, the evidence supporting halos out to at least 100 kpc is much stronger than the opposing evidence.

We have described the halo mass distribution as spherically symmetric. Arguments based on the persistence of the warps in the disks of spiral galaxies have shown that the spiral disks are imbedded in a spherically symmetric potential.[12)] A more recent argument due to Van der Kruit,[13)] also supporting a spherically symmetric mass distribution, is based on the variation of the scale height of stars perpendicular to the disks of spirals and on the velocity dispersion in the z direction. A third argument based on star counts by Monet, Richstone and Schechter[14)] requires that at least one half the mass within the solar circle resides in a spherically distributed component.

We shall use the result that the halo is spherically symmetric in our search for halo optical emission.

III. Optical Observations of Halos

In this section we shall describe the calculation of the surface brightness expected from a halo of M5 stars and compare these results with our observations. We shall use NGC 4565 as a candidate galaxy because it is an edge-on spiral at high galactic latitude and has an accurately measured rotation curve.

Krumm and Salpeter$^{7)}$ have found a flat rotation curve for NGC 4565 with velocity 253 km s^{-1} out to 11.6 arc minutes. Using Equation (1) and the result that the halo mass is spherically distributed, the mass density at radius r, ρ_r, is

$$\rho_r = \frac{v^2}{4\pi G}\frac{1}{r^2} \quad . \tag{3}$$

The mass per unit area, λ_r, integrated along a line of sight which passes a distance r from the galactic center can be seen to be

$$\lambda_r = 2\int_0^{(R_{max}^2-r^2)^{1/2}} \rho_r dz = \frac{v^2}{2\pi G}\frac{1}{r}\tan^{-1}\sqrt{(R_{max}/r)^2 - 1} \quad , \tag{4}$$

where R_{max} is the maximum radius of the halo. The number of stars per unit area at radius r, if each star has mass m_*, is

$$N_r = \lambda_r/m_* . \tag{5}$$

Finally, the surface brightness, measured on a linear scale, of a halo composed of stars of absolute magnitude, M_*, and mass, m_*, at distance, d Mpc, plotted in units of the number of m_o magnitude stars per arc sec^2 is

$$\sigma_r = 10^{\frac{m_o - M_* - 11.34}{2.5}} \times \frac{\left(\frac{v}{250 \text{ kms}^{-1}}\right)^2 \frac{2}{\pi} \tan^{-1} \sqrt{(\theta_{max}/\theta)^2 - 1}}{\theta \, d \, m_*} \qquad (6)$$

Here, θ is in arc minutes and θ_{max} is R_{max} expressed in arc minutes.

Perhaps the most difficult part of evaluating Equation (6) is the determination of the absolute magnitude M_* of a characteristic halo star. The problem is that there is an apparent correlation between stellar luminosity and metal abundance. A sequence of decreasing metal abundances going from disk to old disk to halo stars, is a sequence of decreasing luminosities. Most observations15),16),17) support this trend but Eggen has counterexamples at ~.6 $M_\odot$ for which he shows that the luminosity of stars of different metal abundances are similar. However, most of the data including that of Eggen's support the correlation between metal abundance and luminosity.

The faintest M5 $[(R-I)_K = 1.29]$ star that we have been able to find has an absolute luminosity $M_I = 10.84$ in Kron's photometric system. It is GL 299.3) Using Hoxie theoretical fit to the lower main sequence, we obtain the corresponding mass, $m_* = .14 M_\odot$, which is in good agreement with the available binary star data.

We have tried to determine whether future observations might reveal less luminous M5 stars. GL 299 lies about 2 magnitudes below the Hyades main sequence at a distance modulus of 3.1. Figure 2 of Eggen17) is an HR diagram showing the spheroid and disk populations of the Galaxy. GL 299 lies on the lower edge of an extrapolation of Eggen's spheroid luminosity distribution, which adds confidence to our tentative conclusion that GL 299 is a faint M5 star. One may ask whether the luminosity of GL 299 is characteristic of M5 halo stars with low metal abundances. There is some unpublished work by Vanden Berg18) indicating that halo stars with metal abundances as low as 10^{-5} $Z_\odot$ would have luminosities which are similar to the luminosity of faint stars from the spheroid of the Galaxy. At log T_{eff} = 3.5, which is close to M5, changing the metal abundance from $Z_\odot$ to 10^{-5} $Z_\odot$ results in a 2 magnitude decrease in luminosity, about the same as the spread observed by Eggen. Based on Vanden Berg's models, it appears that we may be able to estimate Population III luminosities reasonably well.

Using GL 299 as our standard M5 star we have plotted in Figure 1 the expected surface brightness for a halo surrounding NGC 4565 in which all of the interior mass is contained in M5 stars. Beyond 4 arc minutes a small fraction of the total mass is contained in the visible disk. The dashed line in Figure 1 is a plot of the expected halo surface brightness for a halo extending out to 150 kpc, or 28 arc minutes, while the solid curve corresponds to a halo of 62 kpc or 11.6 arc minutes. The halo must extend out to at least 11.6 arc minutes since Krumm and Salpeter have measured a rotation curve for NGC 4565 which is flat out to that distance. We have taken the galaxy to be at 18.4 Mpc1) based on its group association and an H_o = 50 kms^{-1} Mpc^{-1}.

Also plotted in Figure 1 are observations of the halo of NGC 4565 taken with the annular scanning photometer. The data were taken with the McGraw-Hill 1.3 m telescope in February and March 1979. The centers of the circular scan paths C and D are 10 arc minutes from the galaxy's center along a line perpendicular to the galactic disk, which is at position angle 134°. Position C is to the northeast, and D is to the southwest. The radius of the scan is 9.0 arc minutes and a 30 arc second circular aperture was used. The data in Figure 1 containing 51,000 scans, has been normalized using a relatively starless sky area close to the galaxy to correct for sky gradients and telescopic effects. This procedure has been discussed in earlier work.19),20) The curve fit to the data is the de Vaucouleurs surface brightness law.

Returning to Figure 1 again, the abscissa is the galactic radius and the ordinate is halo surface brightness in the Kron I band plotted in units of the number of stars of 25.34 magnitude/arc sec^2. On the right side of the figure is the tick mark labelled 10^{-3}. The sky brightness averaged 19.7

magnitudes/arc sec^2 in I Kron during our observing run, and the tick mark refers to 10^{-3} of the sky brightness. Data points have been chosen from regions which are uncontaminated by foreground stars and background galaxies. The error bars are due to photon statistics.

As may be judged from a comparison of the expected surface brightness for a halo of M5 stars and the data, it is highly unlikely that a significant fraction of the halo mass could be contained in M5 stars. No systematic effects that appear plausible would decrease our measured surface brightness though many systematic effects would tend to increase the measured halo signal. Our plotted data has been corrected for known systematics. While our observations exclude the faintest M5 stars, M7 and M8 stars are sufficiently faint so that they cannot be ruled out.

These results may be compared with those of other workers. Hohlfeld and Krumm21) have ruled out M0 or more massive stars based on J band observations of NGC 4565. Dekel and Shaham22) have calculated the surface brightness expected for a halo of NGC 4565 under a variety of assumptions. However, as they point out, it is difficult to deduce firm, model independent conclusions. Bahcall and Soneira23) have used star counts to obtain information about the Galaxy's halo. Though their results may be model dependent, they rule out a halo of M6 or brighter stars.

Some effort has been expended searching for color gradients in the halo as a way of placing limits on a stellar halo component. The problem with this method is that a few giants located in the spheroidal component of a galaxy easily dominate the surface brightness emitted by a faint halo composed of low mass stars. Consequently, searching for color gradients20),24) is a less satisfactory way of obtaining information about a stellar halo component. For example, our earlier color gradient measurements20) were not able to rule out M5 stars.

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REFERENCES

1. Faber, S.M. and Gallagher, J.S. 1979 Ann. Rev. Astron. Astrophys. 17, 135.

2. Peebles, P.J.E. in "Physical Cosmology", ed. R. Balian, J. Audouze, D. Schramm (North Holland, NY 1980).

3. Veeder, G.J. 1975 A. J. 1056.

4. Straka, W.C. 1971 Ap. J. 165, 109.

5. Rogstad, D.H. and Shostak, G.S. 1972 Ap. J. 176, 315.

6. Bosma, A. 1978 PhD thesis Groningen Univ., Groningen.

7. Krumm, N. and Salpeter, E.E. 1979 A. J. 84, 1138.

8. Rubin, V.C., Ford, W.K., Jr. and Thonnard, N. 1978 Ap. J. 225, L107.

9. Turner, E.L. 1976 Ap. J. 208, 304.

10. Peterson, S. 1978 PhD thesis Cornell University, Ithaca.

11. White, S.D.M. and Sharpe, N.A. 1977 Nature 269, 395.

12. Saar, E.M. 1978 In IAU Symposium 84, "The Large-Scale Characteristics of the Galaxy, ed. W.B. Burton.

13. Van der Kruit, P.C. (preprint).

14. Monet, D.G., Richstone, D.O. and Schechter, P.L. 1981 Ap. J. (to be

15. Hartwick, F.D.A., Crampton, D. and Cowley, A.P. 1976, Ap. J. 208, 776.

16. Mould, J.R. and McElroy, D.B. 1978 Ap. J. 220, 935.

17. Eggen, O.J. 1979 Ap. J. 230, 786.

18. Vanden Berg, D. (private communication).

19. Hegyi, D.J. and Gerber, G.L. 1977 Ap. J. (Letters) 218, L7.

20. Hegyi, D.J. and Gerber, G.L. 1979, Proceedings of a Conference on Photometry, Kinematics and Dynamics of Galaxies, ed. D. Evans, Univ. of Texas, Austin.

21. Hohlfeld, R.G. and Krumm, N. (preprint).

22. Dekel, A. and Shaham, J. 1978, Astron. Astrophys. 74, 186.

23. Bahcall, J.N. and Soneira, R.M. 1980 Ap.J. (Letters) 238, L17.

24. Spinrad, H. Ostriker, J.P., Stone, R.P.S., Chin, L-T.G., and Gustavo, B.A. 1978 Ap. J. 225, 56.

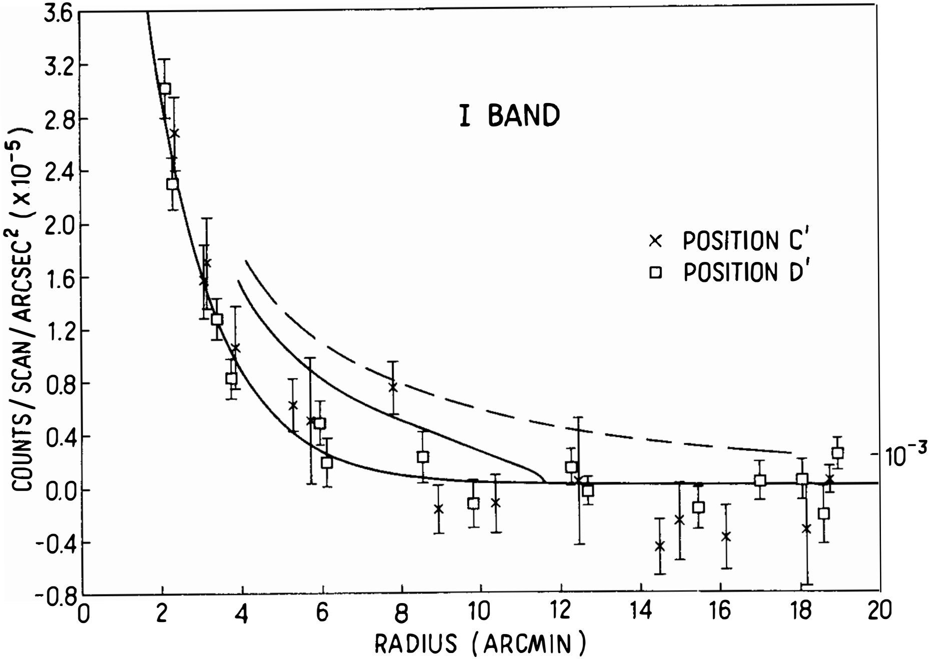

Figure 1. The calculated surface brightness for a halo of M5 subdwarfs and the observations plotted versus galactic radius. The data, in the I Kron band, is for NGC 4565. The dashed line is for a halo of 150 kpc radius, while the solid curve is for a 62 kpc halo. The curve fitted to the data is the de Vaucouleurs's surface brightness law.