THE SEARCH FOR GALAXY HALOS IN THE NEAR-INFRARED

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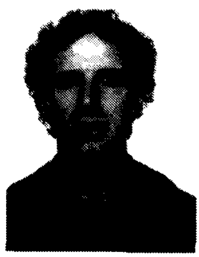


Abstract

In this paper we briefly describe observational studies that have been made to search for near-infrared or optical emission from extended halos in nearby spiral galaxies. We describe our own search for such emission, and report the detection of extended near-infrared emission away from the planes of two edge-on spiral galaxies, NGC 5714 and NGC 5907. The results are broadly consistent with halos dominated by a population of stars at the very lowest masses, possibly extending into the brown dwarf regime.

1 Introduction

The nature of the dark matter in galaxies and galaxy clusters remains unknown, in spite of numerous observational and theoretical studies. One of the leading candidates for galactic dark matter remains low mass stars and/or brown dwarfs, since, as pointed out in a recent review [13], existing observational constraints permit a baryon-dominated dark matter component on these scales.

Many observational searches have been undertaken to look for emission from galactic halos. To date, most have been inconclusive or have yielded only upper limits on the level of such emission. Many of the early studies concentrated on the edge-on Sb spiral, NGC 4565. Two such studies [9], [12] found extended optical emission well away from the plane of of NGC 4565, but this appears [23] to fall off too steeply to trace the dark matter component in this galaxy. Two early searches for near-infrared halo emission [10], [6] failed to detect any such emission, yielding lower limits for the K-band mass-to-light ratio (henceforth M/L) of any halo component of ~40. Similar limits were found [3], [5] for NGC 2683, NGC 4244 and NGC 5907.

Our observational programme began with a study of NGC 100 [7], where we also failed to detect any extended luminous component, and derived upper limits to the near-IR M/L of 60 in the K band and 160 in the J band. This confirmed previous results (e.g.[21], [5]) in indicating that halos, if baryonic, were likely to consist of objects below the hydrogen-burning limit.

However, at about the same time Sackett et al. [18] published an apparent detection of halo emission in deep R band images of another edge-on spiral galaxy, NGC 5907. This new component had an R-band surface brightness of ~ 26 magnitudes/square arcsec at a distance of 1.5 arcmin from the plane of the galaxy. This was greater than could be explained by either the disk or bulge of NGC 5907, and Sackett et al. tentatively interpreted it as the first detection of emission from a galactic halo. Lequeux et al. [15] have also detected halo emission from NGC 5907 in the V and I bands. We now describe our near-infrared observations of this galaxy, and work in progress on one further object, NGC 5714.

NGC 5907 is a spiral galaxy of type Sc, inclined at 87–88° to the line-of-sight, and at a distance of 11.4 Mpc, assuming a Hubble constant of 75 km $s^{-1}Mpc^{-1}$. At this distance 1 arcsec subtends a distance of 55 pc. We adopt the rotation velocity determined by Sancisi and van Albada [19], who measured a value of 220 km s^{-1} at large radii. Their rotation curve has been used in most studies of the mass distribution of NGC 5907 (e.g. [3], [16]). Sofue [22] presents a rotation curve for NGC 5907 which is fairly consistent with that of Sancisi and van Albada, although showing somewhat higher velocities $\sim$250 km s^{-1} at intermediate radii.

As one of the nearest and brightest edge-on disk galaxies, NGC 5907 has been the subject of several observational studies. A detailed study of the mass distributions of the disk and bulge was made by Barnaby and Thronson [3], [4] on the basis of near-IR H-band imaging. By combining these mass models with the measured rotation curves and limits on the extended K-band light [21] they were able to show that the halo of NGC 5907 must have a K-band mass-to-light (M/L) ratio greater than 24 in solar units. Given this, they conclude that low-mass stars could contribute at most 70% of the halo mass, and the remaining mass must be composed of still fainter objects. Another major study of NGC 5907 was undertaken by Morrison et al. [17], who used deep (R$\sim$27 mag/square arcsec), wide field CCD imaging to determine the properties of the disk, including scale-lengths, the existence of a prominent warp, and a clear cutoff in disk luminosity at large radii. They found no evidence for any thick disk component of the type inferred from several studies of the Milky Way, but they do mention an apparent excess of R-band light well away from the disk, which was later investigated more fully by Sackett et al. [18] as described above.

NGC 5714 is also an edge-on Sc spiral, at a redshift of 2237km s^{-1}, giving a distance of about 30 Mpc, and had not previously been observed in galaxy halo searches.

2 Observations

The new observations presented here were taken with the near-IR camera IRCAM3 on the United Kingdom Infrared Telescope (UKIRT) on April 28-30 1995 and May 20-21 1996. IRCAM3 has an SBRC 256$\times$256 pixel InSb array, with a pixel size of 0.286 arcsec^2, giving an overall field of view of 73$\times$73 arcsec^2. The observations were taken through the standard broad-band J and K filters, and conditions were photometric for all observations presented here. Detailed tests on the scattered light performance of the telescope and IRCAM3 were carried out during the May 1996 run.

The basic observing technique was as follows. Two fields (A and B) were defined, with centres 95 arcsec from the nucleus of NGC 5907, above and below the plane of the disk (Figure 1). These A and B positions were observed in a repeated ABBAABB... sequence, with each frame exposure lasting 1 minute. Total integration times were 120 minutes at J and 300 minutes at K for NGC 5907, and 100 minutes and 176 minutes respectively for NGC 5714.

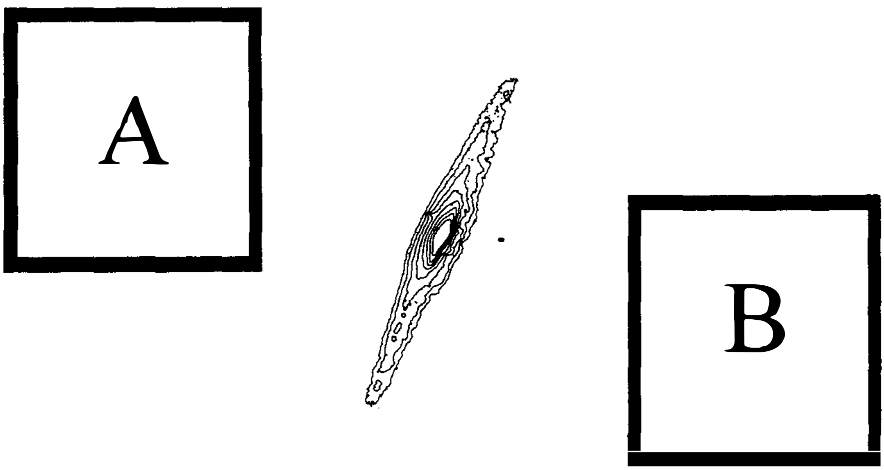


Figure 1: K-band contour map of NGC 5907 showing the A and B imaging positions. The lowest contour is at 16.4 K magnitudes/square arcsec, and the contour interval is 0.2 magnitudes/square arcsec.

3 Data reduction

3.1 Data reduction method

The data reduction method used was identical to that for NGC100 [7]. Briefly, the difference A-B was formed for all pairs of frames, removing most of the sky background, and all of these difference frames were added. A median filtered sky was used to flat-field the final difference frame. Medians were then calculated for strips of pixels parallel to the disk of the galaxy, producing a profile of the surface brightness as a function of height above the disk. Our measurements are only sensitive to the gradient of the surface brightness across the frame and not the absolute value itself. The profiles for NGC 5907 are shown in Figs. 2a and b, and those for NGC 5714 in Figs. 3a and b. The profiles clearly show gradients orthogonal to the galaxy plane, well above the level expected from pixel-to-pixel noise. Regression fits yield gradients of 7.4×10^{-4} and 1.0×10^{-3} counts second^{-1} pixel^{-1} arcsec^{-1} for NGC 5907 at J and K respectively. For NGC 5714 the corresponding numbers are 8.2×10^{-4} and 1.4×10^{-3} counts second^{-1} pixel^{-1} arcsec^{-1}. One count corresponds to 6 photoelectrons.

These gradients could be the result of an instrumental problem, and in order to eliminate this possibility we carried out a number of tests, which we discuss next.

3.2 A null test for detector stability

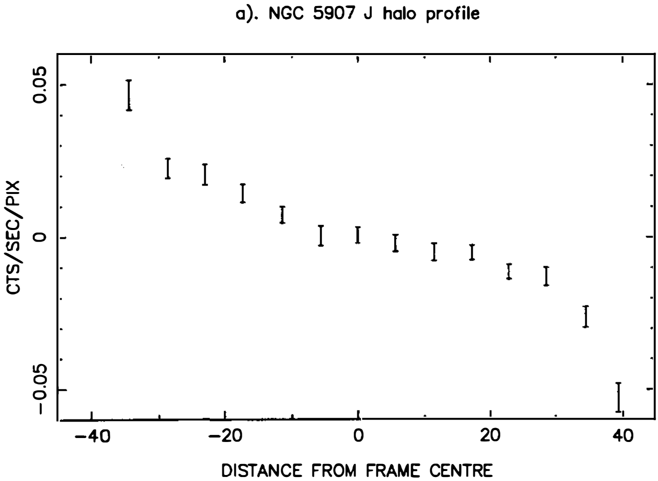
In the observing procedure used, frames were taken in the sequence A,B,B,A,A,B,B etc. The normal reduction procedure then summed A-B pairs to give a final deep difference frame. Now if the observed gradient was purely due to instabilities in the detector array, the effect should be present independently of whether the final frame consists of a sum of A-B frames, A-A, or B-B frames. The last two differences, however, remove any real astronomical structure from the final frame, since they consist of differences of frames taken at the same telescope position, and therefore constitute a null test for array stability. If the array was stable during observing, then these frames should show zero resultant gradient.

A-A and B-B differences were formed and added to give a final coadded frame of the same sensitivity as our real data. This was then examined in an identical way for the presence of any gradient across the detector. The result was that while the noise in the final frame was the same as in our real data, there was no evidence for a systematic gradient in the counts across the frame. A linear regression fit to the NGC 5907 data gave a gradient of 2×10^{-5} counts second^{-1} pixel^{-1} arcsec^{-1}, very much less than the observed gradient and consistent with random noise.

3.3 Scattered light test

Since the measured gradients are very faint, it is important to be able to exclude the possibility that they might be due to scattered light from the galaxy nucleus - 95 arcsec away for NGC 5907. In this case, the concern is not over extended wings in the normal seeing-dominated point spread function, but rather internal scattering within the camera.

To test this possibility, a field near a bright star (α Aqr, $K = 1.0$) was observed in both J and K, at the same spatial offset from the star as was used in NGC 5907. Frames were reduced in the same way as the A and B frames around NGC 5907. The final difference frame showed a gradient of scattered light of amplitude 0.056 and 0.039 counts sec^{-1} pixel^{-1} arcsec^{-1} for J and K respectively. Clearly, measurable scattered flux was indeed present in the camera. However, if these numbers are scaled to the brightness of the NGC 5907 nucleus ($J = 9.5$ and



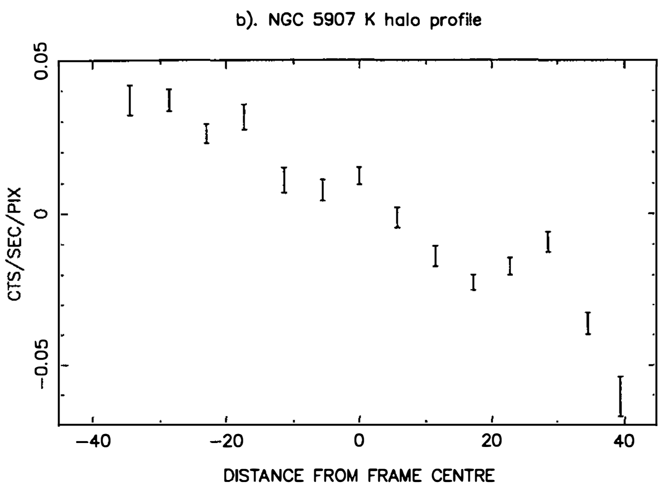


Figure 2: (a) Shows the observed gradient in the J-band for NGC 5907. (b) Same for K-band.

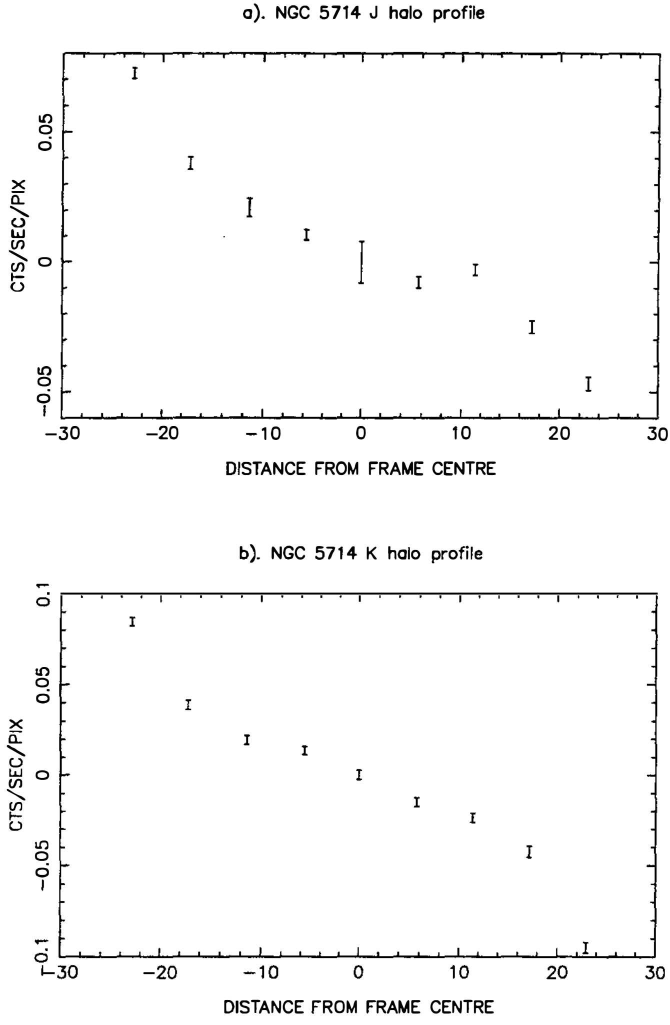


Figure 3: (a) Shows the observed gradient in the J-band for NGC 5714. (b) Same for K-band.

$K = 8.3$ within a 48 arcsec aperture), then the expected gradient due to scattered light becomes 2.9×10^{-5} and 4.7×10^{-5} counts second^{-1} pixel^{-1} arcsec^{-1} for J and K respectively - that is, a factor of $\sim$ 20–30 smaller in both filters than the gradients actually observed in NGC 5907.

In a subsequent observing run for this project in May 1996, we undertook a further test of UKIRT and IRCAM3, to test the effect of an extended object, such as a galaxy, on the scattered light. This was again done using a star, but in this case it was moved to 48 locations around the array, in two strips which mimicked the distribution of disk light from NGC 5907 in the A and B positions described above. The resulting frames were then stacked together to make simulated A and B frames, which were reduced in exactly the same way as the NGC 5907 observations. This process was carried out for two standard stars, BS 6705 and BS 4127 on two nights, both of which yielded simulated gradients which were again a factor 20 too small to explain the observed gradient from NGC 5907, when scaled to take account of differences in brightness and integration. We conclude that it is unlikely that instrumental scattered light could account for the observed gradients around NGC 5907.

For NGC 5714 the same type of scattered light tests yielded less conclusive results. In this case, the observed halo positions were offset only 45 arcsec from the plane of the galaxy due to its higher redshift, resulting in a more significant scattered light problem. In this case, we find that as much as 25–30% of the observed gradient could be due to scattered light, and numbers quoted above have been reduced to account for this factor. The results for NGC 5714 are clearly less secure than those for NGC 5907, and thus we concentrate on the latter in much of the analysis below, but note that there is at least some evidence for a similar component in NGC 5714.

3.4 A further check

Any plausible halo emission would be expected to decrease with distance from the nucleus, so that the observed gradient on our frames should be approximately orthogonal to the galaxy plane. Conversely, there should be little observed gradient parallel to the galaxy plane and this provides another useful check on the integrity of the data. This was a simple test, accomplished by rotating the final A-B frames through 90 degrees and repeating the analysis. The gradients found by linear regression were a factor of 8 less than the gradient orthogonal to the plane and confirm that the surface brightness gradient decreases orthogonally to the planes of the galaxies.

4 Analysis of halo emission

Having established in Section 3 that it is unlikely that instrumental problems can explain the measured near-IR gradients, we search for astrophysical explanations.

4.1 Disk light

The first possibility to test is that we are seeing disk light. The A and B positions for NGC 5907 are centred 95 arcsec above and below the plane of the galaxy, which is $\sim$ 16 times greater than the disk scale-height measured from our K-band imaging of the galaxy. Extrapolating from the measured disk surface brightness, the expected K band gradient at 16 scale-heights is 3.8×10^{-7} counts second^{-1} pixel^{-1} arcsec^{-1}, some 3000 times smaller than the measured gradient. Thus the observed disk is not responsible for the gradient shown in Figure 2. It also appears hard to explain the observations by means of a thick disk, of the type that has been invoked for the

Galaxy. For example, a thick disk with a surface brightness 5% that of the thin disk in the $z = 0$ plane would need a scale-height of 1.6 kpc, 5 times greater than that of the thin disk, to give the measured gradient. Such components have not been seen previously in studies of late-type spirals.

Thus, in the remainder of this section we interpret the J and K gradients found here, and the excess R band emission found by Sackett et al. [18], as coming from a previously unidentified halo component. The main objectives of this analysis are to determine optical-IR colours and mass-to-light (M/L) ratios for this component to constrain the nature of the constituent objects.

4.2 Calculation of mass-to-light ratios

If we identify the detected emission with the component postulated to give rise to the measured flat rotation curve, it is possible to calculate an overall M/L ratio for the objects comprising the halo. We assume a power-law form for the halo, such that the projected mass density falls of with radius as

$$H(r) = H_0 \left(\frac{r}{r_0}\right)^{-\alpha}, \quad (1)$$

where the index α is 1.0 to give a flat rotation curve, and was measured by Sackett et al. to be approximately 1.2 in projection, from their R-band data.

Skrutskie et al. [21] derive an equation for the projected mass through a halo of the above type ($\alpha = 1$) as a function of radius and the amplitude of the rotation velocity of the galaxy. Using a rotation velocity of 220 km s^{-1} and a radius of 5.2 kpc, the projected mass density in this halo is 5.4×10^8 $M_\odot$ kpc^{-2}. To calculate a M/L ratio, we also need to know the J- and K-band surface brightnesses at this radius but, as mentioned previously, our method only yields the surface brightness *gradient* directly. However, if a functional form for the radial profile is assumed, it becomes straightforward to convert between surface brightness and surface brightness gradient. If a power-law surface brightness profile as in equation (1) is assumed, then the gradient is given by

$$H'(r) = -\alpha H(r)/r \quad (2)$$

and thus by measuring $H'(r)$ at a known r, we constrain $\alpha H(r)$.

In this way, and assuming an index α of 1.0 (to be consistent with Skrutskie et al.) we find J- and K-band surface brightnesses at 95 arcsec (5.2 kpc) of 24.3 and 23.0 magnitudes $arcsec^{-2}$ respectively, for NGC 5907. These yield $M/L_J = 220$ and $M/L_K = 100$ in solar units when combined with the projected mass density calculated above. Using the higher value of $\alpha = 1.2$ preferred by Sackett et al. [18] decreases the M/L values by about 20%. For NGC 5714, the corresponding values are $M/L_J = 170$ and $M/L_K = 60$. We should also note that our method is completely insensitive to any constant surface brightness component, and thus an extended central core to the halo would not be detected. This would effectively decrease the M/L values quoted above.

4.3 Halo colours

The J–K colour of our detected halo light can be derived directly from the ratio of the gradients detected in the two bands to be J–K = 1.30 ± 0.3 for NGC 5907, and 1.5 ± 0.3 for NGC 5714. Note that this colour is independent of the assumed form of the halo. However, Lequeux et al. [15] note that the optical colours of the NGC 5907 become redder with radius. This could cause the K gradient, and hence flux, to be underestimated relative to the J values, and the intrinsic J–K colours could thus be even redder than we observe. The quoted errors are conservative estimates of the systematic errors in fitting regression lines to the two gradients. The formal regression errors are much smaller than this.

By combining our measurements with the R band detection of Sackett et al. [18] we can determine an optical-IR colour for the NGC 5907 halo. However, in this case the K surface brightness, and therefore R–K colour, depend on the index assumed for the halo. Taking $\alpha = 1.0$, R–K for the halo is 3.5; for $\alpha = 1.2$, R–K = 3.3.

5 Discussion

At this stage it is not possible to say with any degree of certainty what types of objects could make up the halos of galaxies. However, the detection of emission clearly strengthens the possibility that stars and/or brown dwarfs may constitute these halos, and it is of interest to see whether any such models are consistent with all the observations.

Looking first at the infrared M/L ratios we determine, these are marginally inconsistent with a population consisting of purely hydrogen-burning stars, for which the M/L_K limit is 60 or less at the lowest masses. These values are consistent with the *lower limit* on M/L we derived for NGC 100 [7], where the non-detection of any halo may have been due to the much lower rotation velocity and hence total mass (disk + halo) of NGC 100. However, given the dependence of M/L_K on the assumed functional form of the halo, as well as uncertainties in this ratio for stars at the hydrogen-burning limit, it is plausible that the derived M/L_K ratio might just be consistent with stars at the very lowest end of the main sequence.

The J–K colour, which does not depend on the functional form of the halo, is marginally consistent with that of very low-mass stars, for which the colour is observationally determined. For example, from the study of Leggett [14] stars of spectral type M8 have a J–K of around 1.1, decreasing to 0.9 at M6, compared with 1.3 ± 0.3 in NGC 5907. The R–K colour of 3.5, however, matches somewhat earlier spectral types of around M2–M3. In practice a mixture of spectral types would be expected to be present. For example, an admixture of 0.5 % by number of M0 types to a population of M8 dwarfs would result in J–K and R–K colours close to those observed. The total M/L_K, however, would decrease to around 30 which is clearly inconsistent with the value observed. This could of course be raised back to the observed value, without altering colours, by adding a component of brown dwarfs.

However, it should be pointed out that there are at least two strands of observational evidence which appear to contradict this brown dwarf/low mass star model for galactic halos. One of these is provided by studies of low mass stars in the halo of the Milky Way using images from the Hubble Space Telescope [2], [11], [19]. All of these studies find that only a small fraction ($\lesssim$ 6–15%) of the halo dark matter can be comprised of low mass stars. Whilst these studies do not explicitly exclude brown dwarfs as a significant halo mass component, measurements of the the gravitational lensing properties of Galactic halo objects towards the Large Magellanic Cloud [1] now seem to favour more massive objects, possibly White Dwarfs, with masses of about $0.5^{+0.3}_{-0.2}\,M_\odot$.

It is always possible that the light detected by the present study and by Sackett et al. [18] does not result directly from the massive halo population. Fuchs [8] uses a simple dynamical model to show that a luminous halo with an initially steep power-law distribution $\alpha \sim 3.5$ will tend to develop a more flattened extended spatial distribution under the influence of a dark matter potential. Such an extended visible halo could thus trace the dark matter distribution, even if the halo mass were dominated by, for example, completely invisible massive particles.

6 Conclusions

We have detected near-IR J- and K-band emission well above and below the plane of the edge-on disk galaxy NGC 5907, and have possibly detected a similar component in NGC 5714. Such emission cannot arise from the measured disk, and is unlikely to be due to a thick disk component.

If we interpret the detected emission from NGC 5907 as being due to a halo stellar population which contributes the mass required to give the measured rotation curve, then the M/L ratios and the near-IR colours appear to be dominated by stars at the lowest mass limits for hydrogen burning; and the optical- infrared colours require the presence of at least some higher-mass stars in the halo.

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