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V- and I-band observations of the halo of NGC 5907*

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Abstract. Using long exposures taken in the V and I bands with a 4096×4096 pixel CCD array at the prime focus of the Canada-France-Hawaii telescope, we have confirmed the discovery by Sackett et al. (1994) of a flat, faint luminous halo around the edge-on Sc galaxy NGC 5907. This halo is redder than the disk. Its nature is still an observational challenge. We suggest however that its color can only be accounted for by stars less massive than $0.8 M_{\odot}$. Their total mass in NGC 5907 is very uncertain, but it might possibly account for the excess dynamical mass in this galaxy. Alternatively their distribution might trace the dark potential without contributing significantly to the mass. We give upper limits to the extinction by an hypothetical dust in the halo.

Key words: galaxies: NGC 5907 - galaxies: halos - galaxies: photometry - galaxies: stellar content - galaxies: structure - dark matter

1. Introduction

The presence of dark matter in spiral galaxies has long been inferred from their flat rotation curves. Amongst the possible candidates for this dark matter, low-mass stars and brown dwarfs are seriously considered. While brown dwarfs are almost invisible optically, there is a chance that the most massive amongst the low-mass stars can be detected directly. Recently, Sackett et al. (1994), hereafter SMHB, have found that the edge-on Sc galaxy NGC 5907, which has the usual problem of dark matter (Sancisi & van Albada 1987; Barnaby & Thronson 1994, hereafter BT), is surrounded by a faint luminous halo. This halo might be rather flat since it was detected only to 6 kpc from the plane of the galaxy. Very recently, James & Casali (1996), hereafter JC, have reported a surface brightness gradient

perpendicular to the disk of the galaxy in the J and K bands. We discuss here the results of very deep exposures of NGC 5907 in the V and I bands at the prime focus of the Canada-France-Hawaii telescope (CFHT) with the wide-field camera MOCAM. Section 2 describes these observations and their reduction, Section 3 presents the results and Section 4 is a discussion. Another product of our observations is an upper limit to the amount of dust around NGC 5907, presented in the Appendix.

2. Observations and reductions

The observations were made with MOCAM, a mosaic of four 2048×2048 pixel anti-blooming CCDs at the prime focus of the CFHT, with a field of view of $14' \times 14'$ at a scale of $0''.206$ per pixel (Cuillandre et al. 1996). 5×30 -m V frames and 9×20 -m I_{Cousins} frames were obtained in good photometric conditions, totalling exposure times of 2 h 30 m and 3 h respectively. The frames were taken with slight shifts with respect to each other to allow elimination of the spurious events during the reduction of the data through a median stacking of the images. The image quality is better than $1''$ for the final V frame and $0''.9$ for the final I frame. The flat-field applied to each frame was built from the combination of all empty fields frames taken with MOCAM during the same new-moon period as our observations (about 15 I and 15 V frames). The instrument set-up was not modified during the whole period. The same part of the calibration field SA 110 (Landolt 1992) was first observed on each of the four CCDs, then the whole field on the full camera, giving an internal check of the quality of the reference stars: the photometric error is of the order of 0.03 mag. in each band. Each CCD is different because the gain of the amplifier in the reading chain varies slightly from chip to chip. A small correction was secured by measuring the sky background on the edges of each CCD and by multiplying each CCD frame by a factor such that all these sky backgrounds are at the same level. The sky level measured after reduction was $21.50 \text{ mag. arcsec}^{-2}$ in V and $19.23 \text{ mag. arcsec}^{-2}$ in

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* Based on data obtained with the CFHT in Hawaii

I, in excellent agreement with the mean values for photometric nights at Mauna Kea, respectively 21.5 and 19.2.

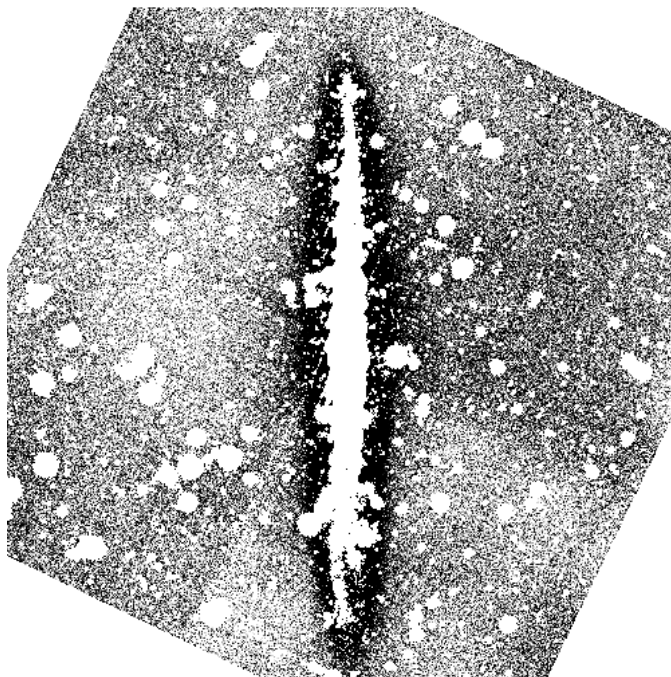


Fig. 1. The masked I image of NGC 5907. The size of the frame is $14' \times 14'$. North to the upper right edge of the CCD frame, East to the right. Note the mask applied to all bright objects, and the large-scale irregularities of the background.

Several difficulties arise when one wants to reach levels of the order of 10^{-3} of the sky background. One is visible on fig.1: the background is not fully uniform up to 3 times this level at large scales, in a way not reproducible from frame to frame. This is due to non-uniform scattered light in the camera, the telescope and the dome. No correction is possible without a dedicated effort to get a low instrumental scattered-light level as in coronagraphs. This effect is the ultimate limitation of our observations. In this respect this situation is similar to that in the observations of Morrison et al. (1994), hereafter MBH.

The second effect is the existence of faint extended wings in the Point Spread Function (PSF), presumably resulting from reflections between the CCD and the dewar window, and from scattering on the optical surfaces. This effect is a serious limitation and we have studied it in details. We built the PSFs in V and I to a radius of $16''$ where levels of 10^{-7} of the central pixel are reached, using a procedure similar to that described by MBH, Sect. 3.3.4. Both PSFs exhibit approximate circular symmetry. Their central parts are very well approximated by gaussians and their faint wings have a power-law shape.

We now discuss the different steps of data processing. A faint halo similar to that measured by SMHB is visible on our frames, especially the I one (fig. 1). The first step

is to assess the reality of this halo, which a priori might be due to diffused light. A simple way to check this is to convolve the image with the full PSF, to convolve it also with the gaussian central part of the PSF only, and to interpret the differences between these two convolved images: this gives a very good approximation of the diffused light level. We have checked in this way that long-range contamination by light diffused from the body of the galaxy is actually negligible, as claimed by MBH. In order to avoid contamination by the scattered light around individual stars and galaxies in the field, we have numerically masked their surroundings wherever the level of scattered light estimated from the PSF is larger than 2 times the r.m.s. deviation of the (unfiltered) background. The result is illustrated on fig. 1, where the masked parts of the field appear blank. This procedure also eliminates the bright parts of the galaxy: photometry of these parts is done from the unmasked image.

After eliminating the masked parts and the remaining faint stars and galaxies, we have averaged the surface brightness in rectangles parallel to the major axis of NGC 5907. The position of the major axis has been determined from an elliptical fit of the galaxy at relatively low brightness levels, and the galaxy image has been rotated so that its major axis is the y axis (fig. 1). The long side of the rectangles (along the y axis) measures $373 \text{ pixels} = 1.2' = 4.1 \text{ kpc}$ and has the same length as in SMHB in order to ease the comparison with their work (we use the same distance of 11 Mpc to the galaxy). The length of the short side of the rectangles varies according to the distance to the major axis (see fig. 2).

3. Results

Figure 2 presents the surface brightness profiles of NGC 5907 for some of the cuts defined in the previous section. As explained previously the limitation is the large-scale systematic residual flat-field variations in the background which has to be extrapolated under the galaxy image. The profiles are not completely symmetric with respect to the major axis, perhaps due to a warp and to the fact that the galaxy is not strictly edge-on but has an inclination of $\approx 87^\circ$.

Figure 3 shows the V-I profile perpendicular to the plane of the galaxy, averaged over the three central cuts. The central dust band appears clearly through its redder color. Aside from this band, the disk has $V-I \approx 1.0$, a normal color for undisturbed spirals (de Jong & van der Kruit 1994), and by comparison with SMHB $V-R = 0.65$ and $R-I = 0.35$. $V-I$ becomes bluer by $\approx 0.2 \text{ mag.}$ towards the edges as observed in many spirals by Peletier et al. (1995). However $V-I$ becomes redder at increasing distances from the plane to reach $V-I \approx 1.35$ at about 4.5 kpc. It seems to increase even further at higher z, but the data become unreliable there. This is true all along the disk of NGC 5907. At $z = 4.5 \text{ kpc}$ we obtain by com-

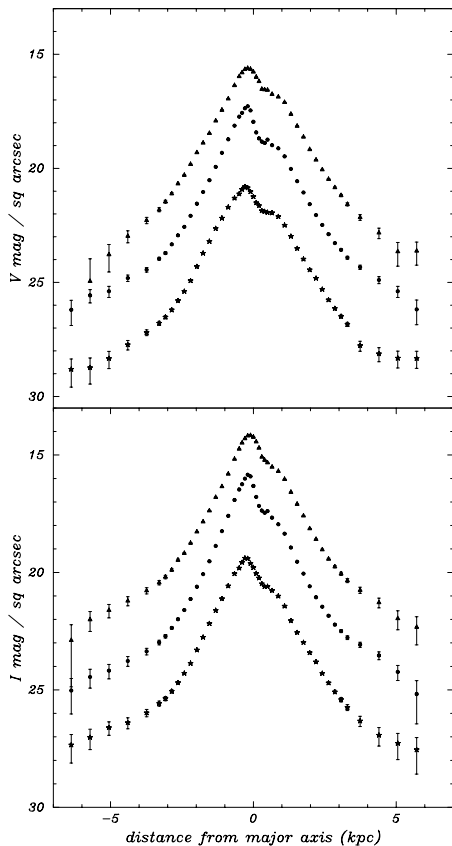


Fig. 2. V (top) and I (bottom) surface brightness profiles perpendicular to the major axis of NGC 5907. The magnitude scale corresponds to the lower profile of each set, the other profiles being shifted upwards by 2.5 and 5 mag, respectively. Each profile corresponds to brightnesses averaged over 4.1 kpc parallel to the major axis. The lower profile is centered 4.1 kpc below the center of the galaxy, the middle profile at the center and the upper profile 4.1 kpc above the center. The distance to the galaxy is taken as 11.0 Mpc. The errors bars are estimates of the effect of extrapolation of the space-variable background.

parison with SMHB $V-R \approx 1.2$ and $R-I \approx 0.1$. We have checked by binning our original data to the larger pixel size of SMHB and reprocessing the images that the measurements of surface brightness in the region of interest are essentially unaffected by the sampling.

4. Discussion

Our data clearly confirm the existence of a faint light emission at large distances from the disk of NGC 5907, first reported by SMHB. Is it due to a luminous halo? To check this point we have built models of the light distribution in NGC 5907 based on previous work, mainly by van der Kruit & Searle (1982), BT, MBH and Fuchs (1995). The comparison with our observations confirms the finding of SMHB: it is impossible to account for the light emission

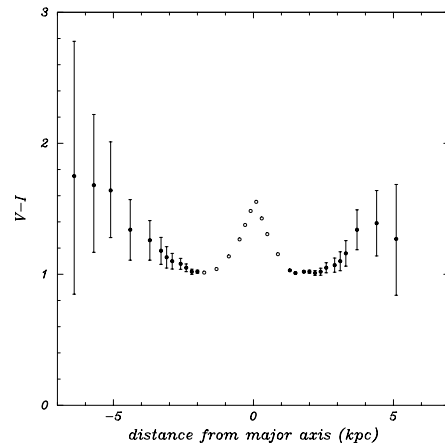


Fig. 3. The $V-I_{\text{Cousins}}$ profile perpendicular to the major axis of NGC 5907. This profile corresponds to an average over the three cuts of fig. 2. The errors bars result from the addition of the uncertainties in fig. 2

above $z \approx 3.3$ kpc without adding a halo emission. But the emission might also be possibly due to a faint extension of the bulge if its ellipticity increases with radius (note that the distinction between bulge and halo then becomes semantic). Another possibility is that the galaxy presents a very large-scale warp parallel to the plane of the sky. However such a warp is expected to have a color $V-I \approx 0.8$ as the outer disk, rather than being redder than the disk. Thus we believe that the halo emission is real and is redder than the unabsorbed parts of the disk.

A gradient in surface brightness corresponding to the luminous halo has been found independently by JC in the J and the K band within $3.2 \leq |z| \leq 6.9$ kpc above the center of the galaxy. Their method does not yield a value for the surface brightness, but they obtain a color $J-K = 1.3 \pm 0.3$ in this region from a comparison between the gradient in J and in K. However our observation shows a strong color gradient in $V-I$. If such a gradient also exists in $J-K$, this may affect their determination of the color. Assuming that the light is pure halo light and that it is not affected by interstellar reddening (see appendix), it is possible to derive some conclusions about the stellar population which is presumably responsible for the emission.

i) Any stellar population of any age $\leq 1.5 \cdot 10^{10}$ yr with a “normal” initial mass function (hence dominated by giants) has $J-K \leq 1.0$, a value only reached for old populations with solar or super-solar metallicities (Buzzoni 1989). The same is true for isolated main-sequence stars (Kirkpatrick et al. 1993, Allard & Hauschildt 1995: fig. 13). As a high metallicity is unlikely for halo stars, we conclude that the determination of $J-K$ of JC may have problems due to the probable color gradient (see above).

ii) The $V-I$ color of the halo may be appreciably redder than the value of ≈ 1.35 we measure at 4.5 kpc. We

have hints for redder colors at larger distances, and the measurements at 4.5 kpc may still be contaminated by a warp in the disk. Taking the measured color at face value, it is similar to that of metal-rich elliptical galaxies (see e.g. Poulain & Nieto 1994). A high metallicity being unlikely for a halo, the stellar population is rather dominated by stars with mass lower than $0.8 M_{\odot}$, implying a cut-off in the initial mass function since all stars with such masses are still on the main sequence whatever their ages. We already found a similar result for the outer bulge of NGC 7814 (Lequeux et al. 1995). The visible luminosity and color of such a population is dominated by the most massive stars. For a given color, their mass and luminosity depend much of their metallicity. For a typical 1/100 solar halo metallicity, a V–I of 1.35 corresponds to 12 Gyr-old stars of $0.15 M_{\odot}$ with $M_I \approx 10$ (G. Chabrier, private communication). $\mu_I \approx 26 \text{ mag. arcsec}^{-2}$ corresponds to $2.5 \cdot 10^7 M_{\odot} \text{ kpc}^{-2}$ if only these stars are present. This is considerably lower than the $4 \cdot 10^8 M_{\odot} \text{ kpc}^{-2}$ required for the minimum spherical massive halo solution of BT. But this is a strict lower limit, and one could easily reconcile the masses by adding lower-mass stars which contribute little to the luminosity. Alternatively, the faint luminous halo could just be a natural dynamical signature of the existence of a dark halo of different nature as suggested by Fuchs (1995). Another possibility is that the faint light corresponds to a flattened extension of the bulge with a de Vaucouleurs $r^{1/4}$ law which would fit well the outer profiles of fig. 2. Unfortunately our measurements at large galactocentric radii are of insufficient quality to check this.

An interesting problem is the origin of the truncated mass function of the very red stars. No dynamical process at the scale of galaxies can sort out stars by mass, because the corresponding relaxation times are much longer than the age of the Universe. Consequently the stars must have been formed with their present mass function.

5. Conclusions

We have confirmed the detection by Sackett et al. (1994) of a faint luminous halo around NGC 5907. This halo is very red and can only contain stars definitely less massive than the limit for the mass of 15 Gyr-old main-sequence stars, about $0.8 M_{\odot}$. The actual value of their mass is unfortunately very dependent on their metallicity. It is not impossible, as suggested by SMHB, that such stars account for the missing mass in NGC 5907. But the visible halo could also trace the dark matter of a halo of different nature (Fuchs 1995). The truncated mass function of these stars must be the outcome of star formation itself. This is reminiscent of the problem of cooling flows around massive galaxies in clusters, which if they really exist can only form low-mass stars. It could be related to the formation of the bulge, as perhaps in NGC 7814 (Lequeux et al. 1995).

The present results are preliminary and must be confirmed by observations using special procedures for reduc-

ing the effect of the scattered light at very faint surface brightness levels.

Appendix: determination of extinction. We used the algorithm SExtractor (Bertin & Arnouts 1996) to separate background galaxies from stars in both I and V frames, and measured the V–I color of galaxies in the same way as described in Lequeux et al. (1995). We then averaged the colors on $1'$ wide strips parallel to the major axis of NGC 5907. The r.m.s. error on the averaged colors, due to the intrinsic color dispersion of the galaxies, is about 0.025 mag. The galaxies in the central strip are redder as expected, by 0.09 mag., a 2.8σ effect. Those in the next strip centered on the right side (see fig. 2) are marginally redder by 0.07 mag., at 2.5σ , possibly indicating dust in a warp. All the other strips have the same average V–I within the uncertainties, showing that there is no significant extinction gradient in the observed part of the halo of NGC 5907. It is clear that the V–I color excess in the optical halo cannot be greater than 0.1 mag. at most, so that it can be neglected.

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