NGC 5907 revisited: a stellar halo formed by cannibalism? *

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Abstract. We report on further observations of the luminous halo of NGC 5907. New V, I and B deep photometry confirms the existence of an extended stellar halo redder than the disk. Our data are consistent with a faint halo, or very thick disk, composed of a metal-rich old stellar population. We propose that it could be the remnant of a merged small elliptical, and we support our hypothesis with N-body simulations.

Key words: galaxies: NGC 5907 - galaxies: interactions - galaxies: kinematics and dynamics - galaxies: photometry - galaxies: abundances - galaxies: halos

1. Introduction

Sackett et al. (1994, hereafter SMHB) have found that the edge–on spiral galaxy NGC 5907 is surrounded by a faint halo in the optical R band. The existence of this halo has been confirmed by several authors at other wavelengths. Lequeux et al. (1996, hereafter Paper I), have observed this halo in two other bands, V and I, and suggest that it becomes redder at increasing distances from the plane of the galaxy. Rudy et al. (1997) and James & Casali (1996) have also detected the halo in J and K; the combination of their brightnesses with those of SMHB and of Paper I gives results difficult to understand. The halo of NGC 5907 is clearly stellar in origin but its nature is still unknown. Its relatively red V-I color implies either a normal, metal-rich, old stellar population, or if the stars are metal-poor an initial mass function favoring extremely low masses (see discussion in Paper I). The observations being very difficult because of the faintness of the halo, we decided to perform new observations, described in Sect. 2 and 3. To interpret them, Sect. 4 proposes a scenario in which NGC 5907 has encountered and cannibalized a small elliptical galaxy about 2 Gyr ago.

2. Observations

All the observations have been obtained with the Canadian-France-Hawaii Telescope. The V and I observations were made in a single photometric night and used the UH 8k mosaic of CCD at the prime focus. This camera being insensitive in the blue, the B observations were performed during another night with the MOS instrument at the Cassegrain focus, equiped with the STIS-2 2048×2048 pixel CCD camera.

The UH 8k mosaic is made of eight 2048x4096 pixel CCDs arranged to form a square. The scale is 0.206 arc second per pixel of 15 $\mu$m, but the pixels were binned so that the final pixels are of 0.412 arc second. We used a position–switch observing mode in order to limit the effects of the changes in the sky background. The image of the galaxy was centered parallel to the longer side of one of the CCDs during half of the exposures, and moved to the parallel CCD during the other half. Consequently, only two of the eight CCDs were used but the field covered by each of them (14' × 7') was sufficient for our purpose. When the galaxy is imaged on one CCD, the other CCD is used for defining the flat field used to reduce the images obtained in the alternative situation. We obtained in each of the V and I Cousins band 9 frames of 480 s each at one position alternating with 9 similar frames at the other position. The frames at a given position were taken with slight shifts with respect to each other in order to allow elimination of the spurious events through a median stacking of the images. The flat fields obtained in this way were of excellent quality and we noticed a significant reduction of the large–scale background irregularities in the final images with respect to the observations of Paper I. This can be attributed to a partial cancellation of the diffuse light by our position–switch technique. The data were calibrated using reference stars in SA 110 (Landolt 1992). The photometric error is of the order of 0.03 magnitude in each band. The sky levels measured on our frame were 21.43 and 19.22 mag.arcsec$^{-2}$ in V and I respectively, in excellent agreement with the mean values for photometric nights at Mauna Kea.

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The B–V color to the right of fig. 1 is also redder than on the other side and might suggest extinction. NGC 5907 is dominated by an old, metal–rich stellar population (see e.g. Poulain & Nieto 1994). The B–V color confirms the result already suggested from the V–I color in Paper I. The colors obtained by combining our B, V and I photometry with the R from SMHB or with the H and K from Rudy et al. (1997) give less consistent results. At 95″ (5.1 kpc) from the plane on the East side one has V–R ≃ 2.0, V–J ≃ 4.3 and V–K ≃ 5.0, with of course very large errors of perhaps 0.5 mag. All these colors are redder by 1–2 mag. than those of elliptical galaxies (respectively about 0.6, 2.3 and 3.2 mag.; Poulain & Nieto 1994; Peletier 1993). The result for V–R is particularly troublesome since the R band lies between V and I. This is probably due to the extreme difficulty of these measurements which are very sensitive to the adopted sky background and to scattered light. In what follows we will only consider our B, V and I photometry.

At larger distances from the plane the colors become redder. They reach V–I = 1.4 at the limit of secure V and I observations (5.5 kpc) and B–V = 1.0 at 4.4 kpc. These colors are typical for an old, metal–rich population (see e.g. Poulain & Nieto 1994). The B–V color confirms the result already suggested from the V–I color in Paper I. The colors obtained by combining our B, V and I photometry with the R from SMHB or with the H and K from Rudy et al. (1997) give less consistent results. At 95″ (5.1 kpc) from the plane on the East side one has V–R ≃ 2.0, V–J ≃ 4.3 and V–K ≃ 5.0, with of course very large errors of perhaps 0.5 mag. All these colors are redder by 1–2 mag. than those of elliptical galaxies (respectively about 0.6, 2.3 and 3.2 mag.; Poulain & Nieto 1994; Peletier 1993). The result for V–R is particularly troublesome since the R band lies between V and I. This is probably due to the extreme difficulty of these measurements which are very sensitive to the adopted sky background and to scattered light. In what follows we will only consider our B, V and I photometry.

Then our conclusions are the same as in Paper I. Either the halo light at a large distance from the plane of NGC 5907 is dominated by an old, metal–rich stellar population, or if the stars are more metal–poor as expected for halo stars, their mass function should be strongly dominated by very low mass stars of 0.15 M⊙ or less. The latter hypothesis looks rather arbitrary, although it would help to solve the problem of the dark matter in NGC 5907. Consequently we prefer the former hypothesis, but now the problem is to understand how a metal–rich, old population can populate the thick system for which we observe the corresponding colors. We will show now that this is possible as the result of capture of a small elliptical galaxy by a large spiral.
Table 1. Parameters of the simulation

|                | scale-length (kpc) | total mass $(10^9 M_\odot)$ | N (particles) |
|----------------|-------------------|-------------------------------|---------------|
| NGC 5907 Bulge| 1.                | 13.6                          | 6723          |
| Disk          | 6.                | 113.                          | 56023         |
| Halo          | 20.               | 181.                          | 89638         |
| Total         |                   | 307.                          | 154384        |
| Companion     | 6.                | 30.7                          | 15238         |
| Grand Total   |                   | 338.                          | 167622        |

Fig. 2. Rotation curves from the relaxed initial state of the simulation (full line), and the final state (dash-dot), compared to the observations (stars and error bars from Sancisi & van Albada 1987) and to the analytical curves obtained from the various components (dashed lines).

Fig. 3. Initial configuration; only the visible matter is shown (face-on and edge-on views). One out of 10 particles is plotted.

4. Merging a small elliptical galaxy with a large spiral

In order to check this idea, we performed a single N-body simulation of this capture. The code used was the treecode from Barnes & Hut (1986, 1989). Table 1 summarizes the initial conditions, i.e. the scale-length and total mass of each component. All components were truncated at a radius of 32 kpc. The main galaxy (simulating the late-type spiral NGC 5907) was composed of a non-rotating bulge, represented by a Plummer component, an $n = 1$ Toomre stellar disk, thickened by a sech$^2$ $z$-distribution with a constant scale height of $z_0 = 500$ pc, and a spherical Plummer halo. The program computes the combined potential of all components for the main galaxy, and solves the Jeans equations to derive the initial rotational velocity and dispersion. The stellar disk was launched with a Toomre parameter $Q$ slightly decreasing with radius, from 1.5 at the center to 1 at the end of the disk. Initially the disk is mildly unstable against spiral and bar formation. The resulting rotation curve is compatible with the observed one (Sancisi & van Albada 1987), as shown in figure 2. The companion is represented by a spherical Plummer component, without dark halo. Its mass is one tenth of that of NGC 5907. It is launched at 32 kpc radius from NGC 5907, with a purely tangential velocity of 200 km s$^{-1}$, in a bound, almost circular orbit. The initial configuration is displayed in fig. 3. Fig. 4 shows some steps of the calculation: 300 Myr after the beginning of the simulation, the elliptical galaxy has triggered a spiral structure in NGC 5907 and starts to be slowed down by dynamical friction. Merging is well advanced 1 Gyr after the beginning, and we stop the simulation after 1.9 Gyr. At this time, the spiral galaxy has restored its flat disk structure, although it is warped and thicker due to the dynamical heating of its stars in the process. This disk is tilted with respect to the original plane due to the conservation of total angular momentum. The elliptical companion has become a fat, hollow and distorted oblate ellipsoid centered on the spiral galaxy and with a rather similar plane of symmetry. This final stage is displayed on fig. 5. Fig. 6 shows a cut through the “visible” particles of both galaxies, perpendicular to the new major axis of the spiral. The elliptical companion dominates the visible mass at heights larger than 4 kpc from the plane, and there the colors should be close to those of the elliptical galaxy as observed. We emphasize that the companion chosen for the experiment is 5-10 times more massive than what is needed to explain the observations; this choice was necessary to remedy the small dynamical range of N-body simulations, but is still indicative of the dynamical phenomenon. Even assuming a constant $M/L$ for the stars of the elliptical, fig. 6 shows that the light does not follow the dark matter profile, although the dark halo density is dominant in this region. In any case, there are many choices for the r- and z-distribution of the dark matter, given a rotation curve, and this experiment shows that the light can be a poor tracer of the dark matter.

5. Conclusions and perspectives

In this paper, we reported on new observations made with the CFH telescope which confirm entirely the conclusions reached in Paper I: the luminous halo around NGC 5907 is redder than the galaxy and has the colors of a metal-rich old stellar population. However discrepancies between
the present observations and others in the literature have to be understood, which require further observations. We have shown by a N–body simulation that this red halo could result from cannibalism of a low–mass elliptical (a few $10^9 M_\odot$) after a slow encounter with NGC 5907.

How frequent is this phenomenon? Nearby spiral galaxies like M 31 often have elliptical companions which might eventually merge with them. Our Galaxy might have cannibalized a satellite which would have produced the thick disk as the result of stellar dynamical heating, the process evidenced by our simulation (Robin et al. 1996). To get statistical information on this capture process, one should conduct a systematic investigation of luminous halos, including measurements of their colors, around a well–defined sample of edge–on spiral galaxies.

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