Stars and gas in the very large interacting galaxy NGC 6872

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Received 13 July 2006 / Accepted 2 November 2006

ABSTRACT

The dynamical evolution of the large (> 100 kpc), barred spiral galaxy NGC 6872 and its small companion IC 4970 in the southern group Pavo is investigated. We present N-body simulations with stars and gas and 21 cm H\textsc{i} observations carried out with the Australia Telescope Compact Array of the large-scale distribution and kinematics of atomic gas. H\textsc{i} is detected toward the companion, corresponding to a gas mass of \(\sim 1.3 \times 10^7 M_\odot\); NGC 6872 contains \(\sim 1.4 \times 10^8 M_\odot\) of H\textsc{i} gas, distributed in an extended rotating disk. Massive concentrations of gas (\(< 10^7 M_\odot\)) are found at the tip of both tidal tails and towards the break seen in the optical northern arm near the companion. We detect no H\textsc{i} counterpart to the X-ray trail between NGC 6872 and NGC 6876, the dominant elliptical galaxy in the Pavo group located \(\sim 8'\) to the southeast. At the sensitivity and the resolution of the observations, there is no sign in the overall H\textsc{i} distribution that NGC 6876 has affected the evolution of NGC 6872. There is no evidence of ram pressure stripping either. The X-ray trail could be due to gravitational focusing of the hot gas in the Pavo group behind NGC 6872 as the galaxy moves supersonically through the hot medium. The simulations of a gravitational interaction with a small nearby companion on a low-inclination prograde passage are able to reproduce most of the observed features of NGC 6872, including the general morphology of the galaxy, the inner bar, the extent of the tidal tails and the thinness of the southern tail.

Key words. galaxies: interaction – galaxies: ISM – ISM: kinematics and dynamics – galaxies: individual: NGC 6872, IC 4970, NGC 6876

1. Introduction

Galaxies with extended tidal tails form an outstanding laboratory to study the effect of a collision on the different components of a galaxy because of the sensitivity of the morphology and kinematics of the tails to the initial distribution of the matter (both luminous and dark) and to the geometry of the interaction (e.g., Dubinski et al. 1999, Springel & White 1999). Early simulations clearly showed that prograde, co-planar encounters are more efficient than retrograde encounters at triggering long thin tails (e.g., Holmberg 1941, Pfleiderer & Siedentopf 1961, Pfleiderer, 1963, Toomre & Toomre, 1972). The tails are made of stars and gas that have been thrown out from the galactic disks during the gravitational interaction which may lead to the merger of the two disks. Spectacular examples of nearby galaxies at different stages of an interaction can be found in the Arp atlas (1966) and the Arp & Madore catalog (1987). The tails are often gas-rich and their kinematics can be traced out to large radii by 21 cm line observations of atomic hydrogen (e.g., Hibbard & van Gorkom, 1993). Some tidal tails contain massive self-gravitating concentrations of matter which may be the progenitors of the so-called tidal dwarf galaxies (Elmegreen et al. 1993, Bournaud et al. 2003, Bournaud et al. 2004). Tidal tails develop not only in merging systems, but also in flyby encounters, where the interacting galaxies do not form a bound system. It is of particular interest to study tidal tails at an early time of the interaction when the two galaxies are well separated and have a clear morphology. A few \(10^5\) yr after closest approach, the tails are already well developed and it is possible to reconstruct the dynamical history of the interaction and examine its influence on the different components of a galaxy and the level of induced star formation.

The southern galaxy NGC 6872 is one of the largest spiral galaxies known. Star formation is traced all along the arms, which extend over more than 100 kpc at our adopted distance of 61 Mpc. The galaxy belongs to a small group, Pavo (see Fig. 1a). NGC 6872 is likely to be affected by tidal perturbations from the nearby companion IC 4970, a small lenticular galaxy located 1'1 to the north. Machacek et al. (2005) have discovered a more than 100 kpc long X-ray trail extending between NGC 6872 and the neighbor galaxy NGC 6876, the dominant elliptical in the group which lies about 8' (~ 142 kpc) to the southeast. The radial velocity of NGC 6876 is about 800 km s\(^{-1}\) lower than that of NGC 6872 (see Table 1). The X-ray tail is hotter (~ 1 keV) than the undisturbed Pavo intergalactic medium (~ 0.5 keV) and has a low metal abundance. The authors interpret the trail as partly due to gravitational focusing of the intracluster gas into a Bondi-Hoyle wake, as the spiral galaxy moves supersonically through the intracluster medium; they point out that the trail could also consist of a mixture of intracluster gas and gas removed from NGC 6872 by turbulent viscous stripping.

The spectacular Very Large Telescope (VLT) multicolor image of NGC 6872/IC 4970 displays striking contrasts between the inner region, especially the straight northern arm, and the blue diffuse tidal tail to the north-east (ESO Press Release 20b/99; see also Fig. 1b, which shows the VLT blue-band image on a grey scale). A bar is clearly seen in the 2MASS \(J, H, K\) images (Jarrett et al. 2003). Fabry-Pérot H\textsc{ii} observations have revealed the presence of ionized gas at the tip of both tails
Table 1. Basic parameters of NGC 6872/IC 4970.

| Parameter         | NGC 6872 | IC 4970 | NGC 6876 |
|-------------------|----------|---------|----------|
| Other names       | ESO 073-IG 32 | ESO 073-IG 33 | ESO 073-IG035 |
| VV 297a           | VV 297b  |         |          |
| AM 2011-705       |          |         |          |
| α(J2000)          | (1) 20°16′56″91 | 20°16′57″87 | 20°18′19″15 |
| δ(J2000)          | (1) −70°44′04″5 | −70°44′57″3 | −70°51′31″7 |
| Type              | (2) SB53P | L.A.-P*  | SB0      |
| Systemic velocity | (2) 4818 km s⁻¹ | 4727 km s⁻¹ | 4010 km s⁻¹ |
| Distance          | (3) 61 Mpc |          |          |
| Scale             | 17.75 kpc arcmin⁻¹ | 296 pc arcsec⁻¹ |          |
| D₂₅              | (2) 6/025=106.9 kpc | 0.676=12 kpc  | 2.8     |
| Position angle    | (2) 66° | 6°      | 79°      |
| Axis ratio        | (2) 0.288=cos(73°) | 0.323=cos(71°) | 0.786=cos(38°) |
| f₀₆₀₆ₐₐₙ        | (4) 1.67 Jy |        |          |
| f₁₀₀₀ₐₐₙ        | (4) 6.61 Jy |        |          |
| T₇₅₆₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈₈¢
2. HI Observations

2.1. Observations and data reduction

HI observations were carried out using the ATCA in five different configurations. Details are given in Table 2. The correlator provided a total bandwidth of 16 MHz divided in 512 channels, which corresponds to a total velocity coverage of 3431 km s\(^{-1}\) and a velocity resolution of 6.7 km s\(^{-1}\). The data were reduced in \textsc{miriad} and \textsc{aips} using standard procedures. After substantial flagging (narrow-band interferences around 1400, 1403 and 1406 MHz plus broad-band solar interference, all affecting the shortest baselines) the data were calibrated using PKS 1934–638 which lies only 8′ away from NGC 6872. The 20-cm continuum emission was subtracted by fitting a first order baseline to all line-free channels. The four good HI line data sets were then Fourier-transformed together using ‘robust’ weighting (ROBUST=0.5). To enhance the signal-to-noise ratio of the HI emission we smoothed the data to a velocity resolution of ∼ 20 km s\(^{-1}\). All velocities are in the barycentric reference frame using the optical definition. The final maps obtained by combining the various data sets have a synthesised beam of 42′′×38′′.8 and a noise level per channel of 0.9 mJy, which is very close to the theoretical value of 0.85 mJy. Moment maps (zeroth order, first and second order) were obtained using signals above 2 mJy beam\(^{-1}\).

HI masses are related to the HI integrated intensities \(\int S_{\text{HI}} \, dv\) (in Jy km s\(^{-1}\)) by:

\[
M(\text{HI})(M_\odot) = 2.36 \times 10^3 D_{\text{Mpc}}^2 \int S_{\text{HI}} \, dv
\]  

(1)

where \(D_{\text{Mpc}}\) is the distance to the galaxy in Mpc.

HI column densities can be derived from the observed integrated intensities by using the relation:

\[
N_{\text{HI}} = \frac{110.4 \times 10^3}{ab} \int S_{\text{HI}} \, dv
\]  

(2)

where \(N_{\text{HI}}\) is the column density of hydrogen atoms in 10\(^{19}\) cm\(^{-2}\) and a and b are the diameters of the synthesised beam at full width half maximum (FWHM) in arcseconds.

2.2. Results

2.2.1. HI distribution

Figures 1b and 2 display the HI distribution as isocontours superimposed on the blue-band VLT image on a grey scale. The atomic gas is confined to the interacting galaxies NGC 6872/IC 4970 and there is no evidence for the presence of extended HI gas around the galaxies or in the region between NGC 6872 and the massive elliptical NGC 6876. We measure an HI flux of 17.5 Jy km s\(^{-1}\) toward NGC 6872/IC 4970, which is less than the published single-dish measurements within...
Fig. 2. Details of the H\textsubscript{i} distribution as contours overlaid on the VLT B-band image, as in the previous figure. The size of the beam is indicated in the lower left corner of the first two frames. Aside from the first frame, all the other frames have the same size. North is up and east is left. The contour levels are the same as in the previous figure. In Figure 4, the H\textsubscript{i} concentrations in the southern tail are labeled S1 to S3 and those in the northern tail N1 and N2. Their H\textsubscript{i} content is given in Table 3.

Fig. 3. H\textsubscript{i} spectrum toward the companion IC 4970.

Table 4 presents the H\textsubscript{i} flux densities in the area bordered by the 15\textquoteleft beam of the Parkes antenna: 20.1 ± 0.5 Jy km s\textsuperscript{-1} (Horellou & Booth 1997); 21.7 Jy km s\textsuperscript{-1} (Meyer et al. 2004 entry HIPASS J2016-770 in the HICAT catalog). Since the single-dish flux is around 21 Jy km s\textsuperscript{-1}, as much as ~ 3.5 Jy km s\textsuperscript{-1} could be distributed in an extended area outside the main galaxies and below the detection limit of our interferometric observations. This corresponds to as much as ~ 3 × 10\textsuperscript{9}M\textsubscript{\odot} of H\textsubscript{i} gas, or 20% the amount of H\textsubscript{i} gas contained in the NGC 6872/IC 4970 system. We can also use the noise level in our maps to estimate the H\textsubscript{i} flux in the area of the X-ray trail, which [Machacek et al. 2005] define as a 4:35 × 5:9 rectangular region between the NGC 6872 and the large elliptical NGC 6876. This area is about 50 times larger than our synthesized beam. From the noise level given in Table 1, we can estimate the noise equivalent flux density in that area as $NEFD = \sqrt{50\sigma} \approx 6.4$ mJy. The radial velocity difference between the two galaxies is $\Delta v \sim 800$ km s\textsuperscript{-1}, which gives a flux $NEFD \times \Delta v = 5.1$ Jy km s\textsuperscript{-1}. This value is clearly too high since it exceeds the difference between the interferometric and the single-dish measurements.

The central region of NGC 6872 is devoid of atomic gas. H\textsubscript{i} was found neither in absorption toward the central continuum source, nor in emission. This is not unusual in spiral galaxies, where most of the gas in the center is often in molecular form. From observations of the CO(J:1-0) line toward the center of NGC 6872, [Horellou & Booth (1997) inferred a mass of molecular hydrogen $M(\text{H}_2)$ of 9.6 × 10\textsuperscript{9}M\textsubscript{\odot} within the central 45\textquoteleft.

The companion galaxy, IC 4970, is clearly detected in H\textsubscript{i} (Fig. 3). It contains ~ 1.3 × 10\textsuperscript{9}M\textsubscript{\odot} of atomic gas.
Fig. 4. Grey-scale map of the H\textsubscript{i} distribution and H\textsubscript{i} spectra measured over several regions in the tails labeled S1, S2 and S3 (southern concentrations) and N1 and N2 (northern concentrations). The first spectrum was measured in the rectangular area around the NGC 6872/IC 4970 system. The solid line refers to the ATCA observations, the dotted line is the single-dish Parkes spectrum of Horellou & Booth (1997) and the dotted-dashed line is the Parkes HIPASS spectrum, which has been shifted by ~40 mJy for clarity. The ten-pointed stars mark the positions of the centers of NGC 6872 and of IC 4970. The location of the star clusters detected by Bastian et al. (2005) is indicated. Star clusters less massive than 10\textsuperscript{6} M\odot are marked by small symbols, and more massive clusters by large symbols. Plus signs and squares correspond to star clusters younger than 100 Myr, and crosses and stars of David to older clusters. The squares and stars of David indicate a large extinction, with A\textsubscript{v} > 1. Note that the regions S1 and S2 at the tip of the southern tail contain only young star clusters.
Five large HI concentrations are seen in the outer parts of NGC 6872, two in the northern tail and three in the southern one. Figure 2 shows that the most northern concentration is spatially roughly coincident with blue stellar clusters. This is also where peaks in the Hα distribution were seen (Mihos et al. 1993). A significant amount of HI is also found near the break in the northeastern arm, close to the nearby companion IC 4970. In the southern tail, the three HI peaks all occur in regions where star clusters are seen in the blue-band image.

There is a clear overall asymmetry in the HI distribution: we estimate that the north-eastern part contains about 1.4 times as much atomic gas as the south-western part. Bastian et al. (2005) estimated a star formation rate of ~ 16.5 M\(_{\odot}\) yr\(^{-1}\) in the north-eastern tail and about half that amount in the western tail, using an empirical relationship between the specific U-band luminosity and the star formation rate measured by Larsen & Richtler (2000). In the center, they inferred a star formation rate about five times lower than in the north-eastern tail.

Finally, we show integrated HI spectra measured in different regions of the galaxy, as illustrated in Figure 3. The regions in the southern tail have been labeled S1 to S3, and those in the northern tail N1 and N2. The amount of gas contained in each region is given in Table 3. Gas at the tip of the southern tail in region S1 produces a narrow HI line (width ~ 100 km s\(^{-1}\)) centered around 5050 km s\(^{-1}\). Emission from the other regions produces broader spectra. In region N2, which lies near the break in the northern arm, there are clearly several velocity components. Region N1 near the tip of the northern arm also exhibits a narrow HI line.

The global HI spectrum integrated over the whole NGC 6872/IC 4970 system is shown in Fig. 4 (first spectrum, upper left). The line is very broad (~ 950 km s\(^{-1}\) at the base), in agreement with the Parkes single-dish HI spectra (Horellou & Booth 1997, Meyer et al. 2004), also shown in Fig. 4. Since Horellou & Booth (1997) used the radio convention \(v_{\text{rad}}/c = \Delta v/\nu\) for velocities, we converted the values to show the spectrum using the optical definition \(v_{\text{opt}}/c = \Delta \lambda/\lambda\) used in the present paper. The low-velocity peak around 4400 km/s seen in the single-dish HI spectra is not seen in the ATCA map.

Also shown in Fig. 4 is the location of the star clusters detected by Bastian et al. (2005). We have divided the star clusters into different groups, depending on their age (more or less than 100 Myr), mass (more or less than 10^6 M\(_{\odot}\)), and extinction (more or less than A, = 1), using the estimates of Bastian et al. (2005) based on the three dimensional spectral energy fitting algorithm of Bik et al. (2003). Interestingly, clusters in the outer regions of the tails (S1, S2, N1, and the region at the very tip of the northern tail) are predominantly young and low-mass and have a low extinction (small plus signs). Some old, low extinction massive clusters (larges crosses) are found north of the northern tail at the border of the HI distribution. Such old massive clusters are also found in the inner region (regions S3 and N3). Several young, low-mass, low-extinction clusters (small plus signs) are found near the companion, slightly to the east, and it is likely that their formation has been triggered in the interaction. Regions S3 and N1 contain large amounts of HI gas, and a collection of star clusters. The young ones (plus signs and boxes) seem to lie at the periphery of the HI concentrations. There is no systematic indication that clusters with higher extinction (boxes) lie closer to the peak of the HI concentration. Star clusters are expected to form from denser, molecular gas which does not necessarily coincide with the more diffuse atomic gas observed here. Also, some clusters may lie in the front part of the HI concentration and not suffer from much extinction. Bastian et al. (2005) found an excellent correlation between the location of the youngest clus-

![Image of Figures 2, 3, and 4 with annotations]

Fig. 5. The HI emission of NGC 6872 overlaid on a grey scale optical image from the Digitized Sky Survey and displayed as channel maps running from 4496 km s\(^{-1}\) (top left panel) to 5116 km s\(^{-1}\) (bottom right panel). Every other channel is shown of the channel maps showing HI emission. North is up and east is left. The levels are 3, 5, 9 mJy/beam. The first contour corresponds to the ~ 3\(\sigma\) level. The synthesized beam is shown in the bottom left corner of the first panel.
In order to narrow down the parameter space we first used a restricted three-body model. 10 000 test particles were distributed in a Miyamoto potential representing a galactic disk. The particles were advanced according to the gravitational eﬀect of the potential of the host galaxy and that of a perturbing companion represented by a rigid Plummer potential moving on a Keplerian orbit. A good match was found for a prograde, parabolic, low-inclination encounter with a companion five times less massive than the primary, in agreement with the ﬁndings of Mihos et al. (1993). Then we carried out self-consistent simulations with stars and gas, as described below.

### 3. N-body simulations

In order to narrow down the parameter space we first used a restricted three-body model. 10 000 test particles were distributed in a Miyamoto potential representing a galactic disk. The particles were advanced according to the gravitational eﬀect of the potential of the host galaxy and that of a perturbing companion represented by a rigid Plummer potential moving on a Keplerian orbit. A good match was found for a prograde, parabolic, low-inclination encounter with a companion five times less massive than the primary, in agreement with the ﬁndings of Mihos et al. (1993). Then we carried out self-consistent simulations with stars and gas, as described below.

#### 3.1. The model

The simulations were performed using a particle-mesh algorithm (FFT3D) that makes use of the properties of Fast Fourier Transforms and of the convolution theorem. The gravitational potential is calculated at the nodes of a three-dimensional 128 × 128 × 64 cartesian grid, providing a resolution of 1 kpc. Effective use is made of the entire grid, rather than of only one eighth

| Region          | \(\int S_{Hd}dv\) [Jy km s\(^{-1}\)] | \(M(HI)\) [\(M_\odot\)] | \(d\) [kpc] |
|-----------------|-------------------------------------|------------------------|------------|
| NGC 6872/IC 4970| 17.5                                | 1.54 \(\times\) 10\(^{10}\) |            |
| NGC 6872        | 16.0                                | 1.41 \(\times\) 10\(^{10}\) |            |
| IC 4970         | 1.46                                | 1.3 \(\times\) 10\(^{9}\)   |            |
| N1              | 1.25                                | 1.1 \(\times\) 10\(^{9}\)   | 17         |
| N2              | 4.40                                | 3.9 \(\times\) 10\(^{9}\)   | 39         |
| S1              | 2.18                                | 1.9 \(\times\) 10\(^{9}\)   | 53         |
| S2              | 1.03                                | 9.0 \(\times\) 10\(^{8}\)   | 34         |
| S3              | 0.86                                | 7.5 \(\times\) 10\(^{8}\)   | 12         |

Table 3. \(H_i\) ﬂuxes and corresponding \(H_i\) masses. The values for NGC 6872 were obtained by subtracting those measured toward the companion from the values measured for the pair. The third column lists the distance on the sky of the peak of the various \(H_i\) concentrations labeled in Fig. 4 to the center of NGC 6872.

#### 2.2.2. \(H_i\) kinematics

We now examine the kinematical information that can be gained from the \(H_i\) maps. Figure 5 shows the velocity channel maps as isovelocity contours superimposed on an optical image. Gas in the north-eastern tail has a lower velocity along the line-of-sight (an heliocentric velocity around 4500 km s\(^{-1}\)) than the south-western tail (around 5100 km s\(^{-1}\)). The line-of-sight velocities vary smoothly across the galaxy and are characteristic of those of a rotating disk.

Figure 6 shows the mean \(H_i\) velocity field (top) and the \(H_i\) velocity dispersion (bottom). Again, the smooth velocity gradient across the galaxy appears clearly. The velocity dispersion map shows a peak on each side of the galaxy’s center. One is located on the concave side near the break of the northern arm. The other one lies south of the main body of the galaxy where the southern tail begins. A region of increased velocity dispersion (∼ 75 km s\(^{-1}\)) coincides with the N1 \(H_i\) concentration in the northern tail.

The simulations were performed using a particle-mesh algorithm (FFT3D) that makes use of the properties of Fast Fourier Transforms and of the convolution theorem. The gravitational potential is calculated at the nodes of a three-dimensional 128 × 128 × 64 cartesian grid, providing a resolution of 1 kpc. Effective use is made of the entire grid, rather than of only one eighth

The companion galaxy is modeled as a rigid body represented by a Plummer potential. The assumption of a rigid structure for the companion is justified insofar as we are interested
Fig. 7. Evolution of the stars (left column) and the gas (right column) in the simulation of NGC 6872/IC 4970. The stars in the bulge of the primary galaxy are shown in red. The system is viewed according to the observed geometry (position angle of 66°, inclination of 73°). The time step between two snapshots is 40 Myr, starting 20 Myr after perigalacticon. The position of the companion is indicated by a star.
in the effect of its passage on the internal structure of the larger galaxy, which is probably little affected by the distortion of the companion.

Setting the units of length and time to 1 kpc and 10$^7$ years, with the gravitational constant $G$ set to 1, gives a unit of mass of $2.22 \times 10^9 M_\odot$. The time step was set to $10^6$ years, and particles were advanced using the leap-frog algorithm. We used 440 000 particles to model the disk and the bulge of the primary galaxy (25% of the particles being initially attributed to the bulge) and 60 000 gas cloud particles. The parameters of the simulation presented here are listed in Table 4.

### Table 4. Parameters of the simulations. The orientation of the main galaxy is given by the angle between the orbital plane and the galactic plane ($15^\circ$) and the angle between the x-axis in the orbital plane and the projection of the vector normal to the main galaxy onto the orbital plane.

| Orbit | Parabolic |
|-------|-----------|
| Mass ratio | 5:1 |
| Main galaxy: | $M_{\text{disk}} = 120$, $a_{\text{disk}} = 3$ |
| mass and scale length | $M_{\text{bulge}} = 30$, $a_{\text{bulge}} = 0.45$ |
| orientation | $M_{\text{halo}} = 90$, $a_{\text{halo}} = 10$ |
| Companion: mass and scale length | $M_c = 48$, $a_c = 1$ |

3.2. Results

Figure 7 displays the evolution of the stars and the gas in the primary galaxy as it is perturbed by the companion passing on a prograde, parabolic orbit. The gas distribution is initially more extended than that of the stars. The time between two snapshots is 40 Myr, starting 20 Myr after closest approach. Despite its small mass (one fifth of the mass of the primary), the companion triggers prominent tidal tails very rapidly. The southern tail on the side of the galaxy opposite to the companion is thinner that the northern tail, where the perturbation is stronger. In the simulation the companion, modeled as a rigid Plummer potential and displayed by a red star, accretes significant amounts of matter (both stars and gas). In the observed system, some diffuse stellar emission is seen between the companion and the northern arm of the primary, but it is not clear that stars or gas have been dragged or have fallen onto the companion. Also, in the simulation the northern arm breaks at the location of the companion, whereas in the observed system both galaxies appear more clearly separated. Aside from those differences, the model is able to reproduce several observed features, including the extent of the tidal tails, the thinness of the southern tail, the central bar, the relative position of the two galaxies. The simulated system resembles the observed one most around 130 Myr after closest approach, as shown in Fig. 8. For that epoch, we also display the velocities of the gas in the simulations (over the whole galaxy in Fig. 9) and in the inner part in Fig. 10. The arrows indicate the direction of the velocity of the gas on the plane of the sky, whereas the colors are related to the velocities along the line-of-sight. The line-of-sight velocities are in good agreement with the observed velocity field. Interestingly, the simulation shows that gas in the outer part of the northern tail moves outward, whereas gas in the inner part moves inward toward the companion.

The results of our simulations generally agree with those of Mihos et al. (1993). The gas is modeled in a similar way, as sticky particles, although in our simulation all gas clouds keep the same mass and do not evolve by coalescence or fragmenta-

4. Discussion

Machacek et al. (2005) discuss several possibilities to explain the diffuse X-ray emission seen between NGC 6872 and the large elliptical galaxy NGC 6876.

As they argue, it is unlikely that the hot gas has been extracted from the elliptical galaxy by tidal interactions because the mass of the gas in the tail is more than three times larger than that contained in the elliptical. Had tidal interactions been at work, their effect would have been seen also in the distribution of the stars in NGC 6876. The isophotes of NGC 6876 are regular: Hubble Space Telescope observations do, however, reveal a slight central depression, which is not due to dust absorption. This has been interpreted as the possible signature of the end product of the merging of two gas-free stellar system, each harboring a massive black hole (Lauer et al. 2002). We can estimate the dynamical mass of NGC 6876 from the observed velocity dispersion of 231 km s$^{-1}$ (Davies et al. 1987) using the relation $M_{\text{vir}} = (5.0 \pm 0.1) \times R_c \sigma^2_c/(LG)$, which is the best-fitting virial relation found for a sample of 25 elliptical and lenticular galaxies from the SAURON sample (Cappellari et al. 2006). Taking the effective radius $R_e = 25.48$ kpc as the half-light radius in the blue-band given in NASA/IPAC Extragalactic Database, we obtain $M_{\text{vir}} = 1.57 \times 10^{12} M_\odot$. The projected distance on the sky between NGC 6872 and NGC 6876 is $\sim 142$ kpc, and the radial velocity difference is about 800 km s$^{-1}$. This gives a timescale of 180 Myr, assuming comparable contributions from the velocity
Fig. 8. Distribution the stars (top figure) and the gas (bottom figure) in the simulation 130 Myr after perigalacticon, when the simulated system resembles the observed one most. The position of the companion is indicated by a star.

Fig. 9. Gas in the simulation 130 Myr after perigalacticon. The arrows indicate the direction of the velocity of the gas clouds projected on the plane of the sky. The colors indicate the velocity range along the line-of-sight, $v_{\text{los}}$: larger than 200 km s$^{-1}$ in red, between 100 and 200 km s$^{-1}$ in orange, between 0 and 100 km s$^{-1}$ in yellow, between −100 and 100 km s$^{-1}$ in green, between −200 and −100 km s$^{-1}$ in blue, less than −200 km s$^{-1}$ in black.

Fig. 10. Gas in the inner part of the simulated galaxy 130 Myr after perigalacticon. The length of the arrows is proportional to the velocity on the plane of the sky. The colors indicate the velocities along the line-of-sight, using the color code as in the previous figure.

In the plane of the sky and the separation along the line-of-sight. If NGC 6872 had passed near NGC 6876, a $\sim 10^{12} M_\odot$ galaxy around 180 Myr ago, it is likely that such an interaction would have left a trace in the HI distribution, which is not observed.

− The X-ray trail could be due to *ram pressure stripping* from NGC 6872 as the spiral galaxy moves supersonically though the hot gas within the Pavo group (Machacek et al. 2005). Ram pressure stripping is known to affect the HI distribution in some galaxies (e.g. Vollmer et al. 2004). However, we do not see any sign of that effect in the observed HI distribution of NGC 6872. Therefore, we cannot infer any information about the motion of NGC 6872 with respect to the surrounding gas in the Pavo group.

− Other mechanisms involving an interaction between the interstellar medium and the intergalactic medium could be at work, such as turbulent viscous stripping (Nulsen 1982), where gas at the interface between the galaxy and the intergalactic medium could be heated. At the resolution of our HI observations, we do not see any evidence for that effect either.

− *Accretion into a Bondi-Hoyle trail* is the most favored hypothesis. Machacek et al. (2005) have calculated the extent of the trail assuming an NFW profile (Navarro et al. 1996) for the dark matter distribution in NGC 6872 with a concentration parameter $c = 15$ and extending until a radius $ca$, where $a$ is the inner radius. An extended halo, with an inner radius $a \approx 20$ kpc, is required to reproduce the observed length of the trail. We have performed the same calculation, using a different profile for the halo, namely the one corresponding to the Plummer potential that we have used in the simulation with a scale length of 10 kpc. As illustrated in Fig. 11 for a Plummer profile the downstream profile of density contrast peaks at a larger distance from the moving halo, and decreases more softly. At a downstream distance $z = -10a$, the density contrast is slightly higher for the Plummer sphere than for the NFW profile. Although the density contrast along the trail is, in principle, sensitive to the density profile of the moving halo, this is difficult to use in practice. This calculation is simplified, based on linearized flow equations, which applies only for small density perturbations and Machacek et al. (2005) point out that the observed temperature ratio between the trail and the intra-cluster gas implies an overdensity larger than one.
3. The simulations of a gravitational interaction with the small nearby companion IC 4970 on a low-inclination prograde passage are able to reproduce most of the observed features of NGC 6872, including the general morphology of the galaxy, the inner bar, the extent of the tidal tails and the thinness of the southern tail.

4. Our simulations do not model the gas environment within the group or the motion of NGC 6872 through the group. Without those interactions we cannot address the hydrodynamic processes, i.e. ram pressure stripping, turbulent viscous stripping, or Bondi-Hoyle accretion, discussed in Section 4. However, together with the H\textsc{i} maps, our simulations provide important constraints on viewing angle, internal velocities, mass and gas distributions for input into future hydrodynamic simulations.

Acknowledgements. We thank the referee for a very thoughtful report. We are grateful to Françoise Combes for providing us a version of the code, to Vassilis Charmandaris for his help with the VLT data, and to John Black for useful comments on the manuscript. We thank E. de Blok, E. Sadler and E. Muller for their help during the H\textsc{i} observations. We thank Chris Mihos for providing us his H\textsc{r} data and Nate Bastian for stimulating discussions. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The H\textsc{i} observations were done with the Australia Telescope Compact Array, which is funded by the Commonwealth of Australia for operations as a National Facility managed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

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