Mass transfer and star formation in the early–type galaxy of a mixed pair, AM 0327-285

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Abstract. We present evidence for a young stellar population component in the early–type member of the E+S galaxy pair AM 0327-285. This young population is consistent with the occurrence of cross–fueling in this interacting system. We used spectroscopy, optical imaging, IRAS data, and stellar population synthesis to study the stellar content in the early-type galaxy. We also attempted to date episodes of star formation in its nuclear region, from population synthesis and basic dynamical considerations. The dominant population is old and metal–rich ($[Z/Z]_\odot$=0.3) while $\sim$ 10% of the flux at 5870 Å arises from a superimposed *young* stellar population with age $\leq 5 \times 10^8$ yr. This age is close to several estimates of the characteristic timescale of the interaction, suggesting that the mass influx associated with this star formation occurred as a result of an earlier phase of the interaction and not as a result of the present geometry of the pair.

Key words: galaxies: elliptical – galaxies: stellar content – galaxies: interactions – galaxies: AM 0327-285

1. Introduction

According to many schemes for galaxy formation, galaxy morphology should depend strongly on the environment in which a galaxy resides and, especially, in which it was formed. Therefore, in pairs of galaxies one expects to find members of similar morphological type (Faber & Gallagher 1979; Dressler 1980; Yamagata 1990). This belief has been challenged by the confirmation of many physically bound 'mixed' pairs of galaxies (i.e., a mixture of early–and late–type galaxies). There is a strong overrepresentation of mixed-morphology pairs among binary galaxies in the Catalog of Isolated Pairs of Galaxies (CPG,

Karachentsev 1972) compared to expectations from randomly selecting galaxies from the general distribution of Hubble types in regions of similar surface density. As many as 150 out of $\sim$600 pairs in the CPG may be of mixed type (Sulentic 1992). Detection of excess far–infrared emission (Xu & Sulentic 1991) and numerous structural peculiarities (Rampazzo & Sulentic 1992) suggest that most of these pairs are physical binaries. Detailed study of these mixed pairs may provide important insights into the evolution of galaxies, especially into whether the ellipticals in these systems are primordial or result from merging in systems of originally higher multiplicity.

It is well established from both observations (at a variety of wavelengths) and numerical simulations that gravitational interaction can play a fundamental role in the secular evolution of galaxies, influencing their star formation, gas content, and chemical evolution (Toomre & Toomre 1972; Sulentic 1976; Larson & Tinsley 1978; Young et al. 1984; Keel et al. 1985; Bushouse et al. 1991; Combes 1992). In strongly interacting galaxies the induced star formation can consume a major portion of the interstellar gas on time scales of a few $\times 10^8$ years (Young et al. 1986; Kennicutt 1992).

Mixed pairs of galaxies are excellent laboratories for the study of interaction in galaxies because they contain a single component, the spiral, that is rich in cold gas. This simplifies interpretation of the interaction because most or all of the cold gas can be traced to an origin in a single galaxy. We have obtained spectra, B and I images, and far–infrared data for a southern mixed pair of galaxies, AM 0327–285, and found evidence for a young stellar population in the early–type component. The age of the young stellar component is consistent with dynamical timescales for the interaction and the pair's morphology, suggesting that this burst of star formation was indeed produced by gas dumped from the spiral into the core of the early–type neighbor. The different forms of data are presented in Sect. 2.

Detailed population analysis of the spectrum is presented in Sect. 3, and discussion and interpretation of the data within the cross-fuelling hypothesis are presented in Sect. 4.

2. Data acquisition and analysis

2.1. Imaging

AM 0327–285 is a relatively isolated mixed pair and can be assigned a Lin(br) interaction class in the scheme proposed by Karachentsev (1972). We obtained images in the B and I pass-bands using a TI 800 × 800 CCD at the f/7.5 focus of the CTIO 1.5m telescope in November 1992. On-chip 2 × 2 binning gave an image scale 0.54 arcsec/pixel. For each filter, three exposures were coadded to reduce the influence of ion events and increase the dynamic range of the images. Total integration times were 30 minutes in B and 24 minutes in I. The pair was originally observed as part of a program aimed at measuring the disk opacity of backlit spirals (White & Keel 1992), but the symmetry and geometry of this pair were found unsuitable for such measurements.

The B and I images are shown in Fig. 1 and are marked with the regions studied spectroscopically. The morphology and tidal features of this pair are discussed in detail in Sect. 4. We note at this point that the northern galaxy has some internal structure inconsistent with a pure elliptical classification, so we will refer to it simply as the early–type component. A $B - I$ image is shown in Fig. 2, in which both galaxies show similar nuclear colors $B - I \sim 2.3$ but substantially different color distributions. In particular, the lack of reddening associated with the tidal arm of the spiral may indicate that it crosses behind the early–type galaxy, in contrast with such systems as M51 in which a similar arm produces very strong obscuration. Also, the sign of the radial color gradient in the early–type galaxy is contrary to the norm for ellipticals, indicating that an age gradient may be its dominant cause, rather than a metallicity gradient.

Fine structure in the early–type component was studied through modelling. We produced models for the smooth light distribution of both galaxies in both B and I using the "ellipse" procedure in STSDAS, based on the algorithm outlined by Jedrzewski (1987). Each galaxy was modelled and subtracted iteratively until models for each galaxy were reasonably free of effects of the overlapping light distributions. An image with both models subtracted shows the fine structure so revealed (Fig. 3)

The early–type component has considerable structure when the overall light distribution is subtracted. An S-shaped structure, wound in the same sense as the arms of the spiral component, is prominent crossing the nucleus; it overlaps the outermost arm of the spiral SE of the nucleus, producing some confusion in how to interpret the spiral pattern in this area. The northern part of this pattern is continuous with the faint, narrow tail to the NNE of the galaxy. The excess luminosity in these structures shows a one-to-one correspondence with bluer areas in a color-ratio image; the southern part has a $B - I$ color essentially matching that in the arms of the spiral.

The intensity profile of the early–type galaxy, averaged on elliptical annuli, follows an $r^{1/4}$ law within 10% (0.1 magnitude) over a 5-magnitude range, extending from the 1.5-arcsecond inner limit set by seeing and sampling to the 13-arcsecond radius at which overlap with the spiral is important. Neither the form of the "spiral" pattern seen in excess light nor this profile form is consistent with any kind of normal spiral classification; although disturbed by interaction, this is a system of early Hubble type, originally an elliptical. Structures of this kind are rarely (if ever) found in isolated, undistorted galaxies, lending (circumstantial) evidence that this is more than a prijected pairing of galaxies.

The total light in the S-pattern is small, only 1% at B and about 0.2% at I; these are somewhat uncertain because of the lengthy modelling process needed to isolate the structure. This suggests a typical $B - I$ for the feature (where it is brightest south of the nucleus) near 0.7, as usual for spiral arms and actively star-forming regions. The color maps and structural features imply considerable star formation in some regions of the early–type galaxy, while the rudimentary spiral pattern and outer tidal features suggest that this has its origin in a gaseous disk captured (at some point) by the galaxy.

The morphological evidence for a gas-rich disk consists of the spiral pattern of blue starlight, suggesting a wave in a disk; of the narrow tidal features to the NNE and (faintly) SW of the galaxy; and of a shell–like structure extending between position angles 5° and 50°. This may represent the first phase–wrapping of material which has passed through the core, and appears as a sharp shell only when one of the systems is dynamically cool as in a disk (Quinn 1984).

When did the galaxy acquire this material, and was it from the bright spiral or some fainter former companion? The extent of tidal debris and the apparent shell's radius are similar to the scale of the current pair separation; these are all on broadly similar timescales. The strong grand–design pattern of S suggests that the early–type galaxy is in a direct orbit inclined significantly to the disk plane, but not close to the poles (see Sect. 4).

The integrated luminosity ratio of the galaxies (from the smooth models) is 2.36 in B (S:E) and 1.76 in I; the mass ratio should be close to unity given the overall color differences.

The model subtraction also shows interesting structure in the spiral component. The spiral structure may be traced with less ambiguity, especially in the region of overlap with its companion. Inside the region of strong grand-design spiral structure, there is evidence of an elliptical ring and some trace of a bar within, and perpendicular to, this ring. Such features are seen in models of the response of a self-gravitating disk to tidal perturbation (Gerin et al. 1990), resulting from swing amplification. The perpendicular alignment of ring and bar is generally characteristic of a system in which the so-called X2 orbits are populated.

2.2. Spectroscopy

Long–slit spectra were taken with the Boller and Chivens Cassegrain spectrograph at the ESO 1.52m telescope (La Silla)
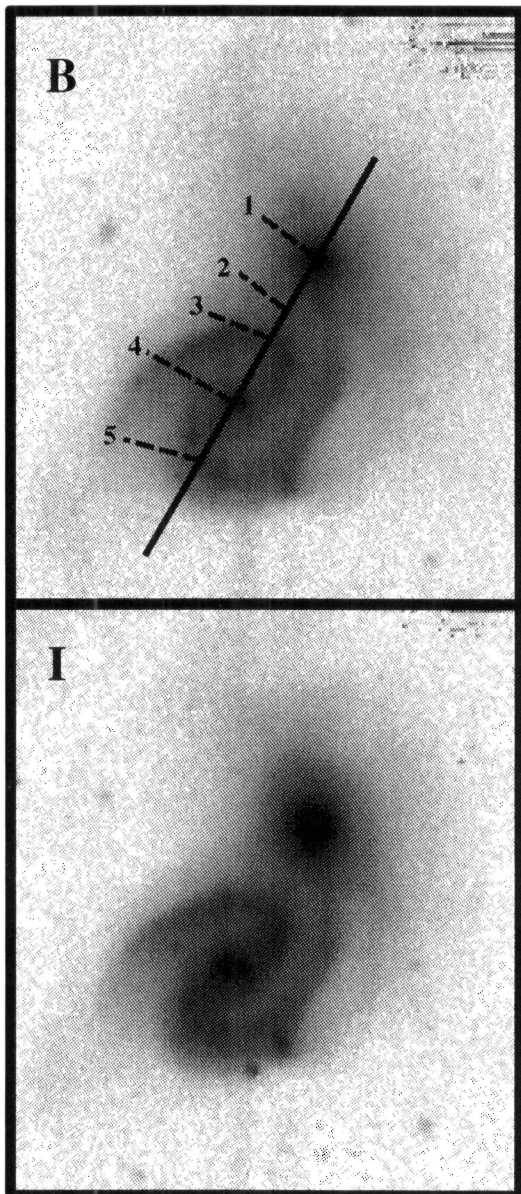
Fig. 1. B and I images of AM 0327–285 , from the CTIO 1.5m telescope. They are displayed with a nonlinear intensity mapping, to show features over a wide dynamic range. The slit position used for the ESO spectrum is marked with the locations extracted for Fig. 5. Noth is at the top, east to the left; the field size for each image is 160×184 arcseconds

Fig. 2. $B - I$ color map of AM 0327–285. Darker tones represent redder colors

Fig. 3. B image of AM 0327–285 after subtracting elliptically symmetric models for the light distribution of both galaxies

in December 1991. We used a 300 l mm^{-1} grating in the first order providing a mean dispersion of 253 Å mm^{-1} over the range 3500–11200 Å. The slit width was 2 arcsec for the galaxies and 5 arcsec for the standard stars. The spectra of the two galaxies, E and S, are shown in Fig. 4. The most prominent stellar absorption lines and several emission lines (Hα, [NII]λ6548, 6583 and [SII]λ6717, 6731) can be seen in both galaxies, indicating the existence of ionized gas in the early–type galaxy, a possible sign of mass transfer (de Mello Rabaça et al. 1993).
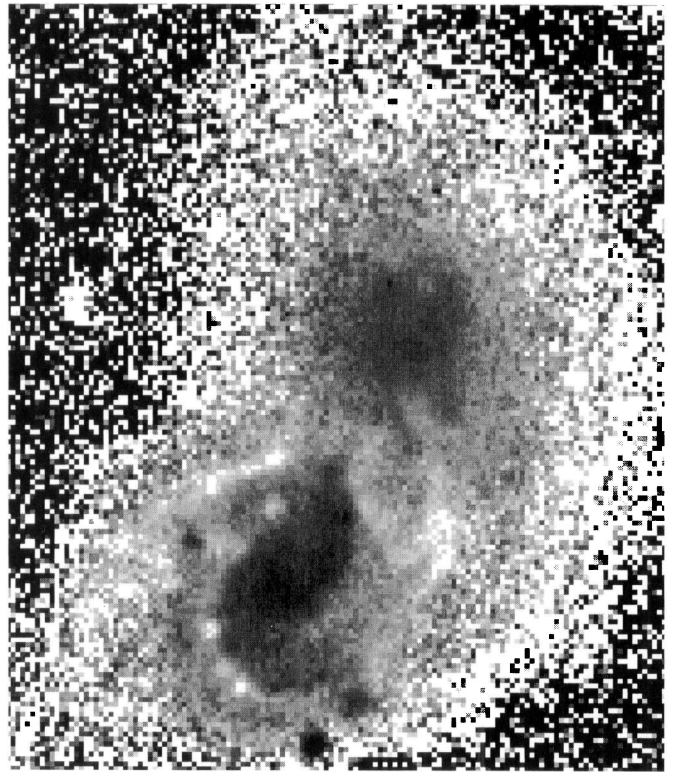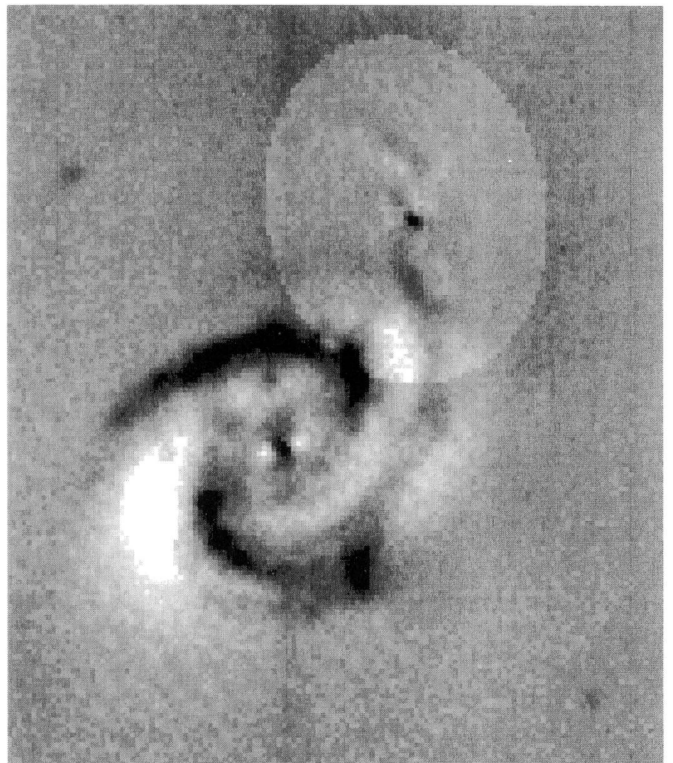
Fig. 4. Nuclear spectra of the early-type and spiral galaxies of AM 0327–285

Fig. 5. A montage of spectra of AM 0327–285 centered on the region of Hα, [N II], and [S II] for 1) the early-type nucleus, 2) region between the early-type and spiral galaxies, 3) near side spiral arm emission knot, 4) spiral nucleus, 5) far side spiral arm emission knot

Figure 5 shows a montage of spectra centered on the region Hα, [N II], and [S II]. We show cuts centered on 1) the E nuclear region, 2) the region between the E and the near side spiral arm emission knot, 3) the spiral arm toward the early-type component, 4) the spiral nucleus, and 5) the spiral arm on the opposite side from the companion. These regions are marked for reference in Fig. 1. Cuts 2 and 4 show [NII] $\lambda6583$/Hα ratios consistent with normal HII regions. The mean redshifts of S and E shown in cuts 1 and 3 are very similar ($cz \sim 11050\,\mathrm{km\,s^{-1}}$). We see line emission spread continuously between the two nuclei, especially in [N II] $\lambda6583$ and the [S II] $\lambda\lambda6717, 6731$ doublet. The distribution of line emission is roughly constant in velocity and appears unlikely to be due to residual night sky emission. The telluric B band immediately redward of [N II] $\lambda6583$ can cause spurious features due to imperfect sky subtraction and resampling, but is unlikely to cause a spurious emission link. In fact, residuals from the B band would more likely weaken any emission-line bridge than produce one artificially. This may be an example of shocked gas flowing between two galactic nuclei.

2.3. IRAS data

The far–infrared (20–400μm) is an especially sensitive wavelength range for detecting current star formation since the most violent (nuclear) star formation tends to take place within highly opaque clouds of dust and molecular gas that convert most of the visible and ultraviolet light into FIR emission. Observations of interacting galaxies with the Infrared Astronomical Satellite (IRAS) show that their FIR emission is enhanced relative to that from non–interacting galaxies (Lonsdale et al. 1984; Cutri & McAlary 1985; Kennicutt et al. 1987; Telesco et al. 1988; Solomon & Sage 1988; Xu & Sulentic 1991), indicating that star formation is stimulated in the interaction process. However, most studies of star formation activity in paired galaxies
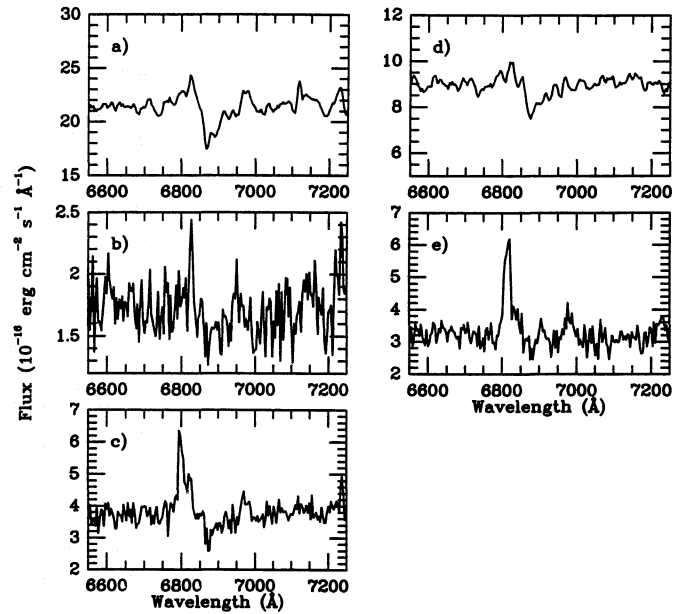
are complicated by the fact that both members of a pair may be infrared sources and the limited resolution of IRAS can cause severe confusion except for the closest or widest examples (Sulentic & de Mello Rabaça 1993; Surace et al. 1993). Therefore, infrared detections from interacting systems with separations smaller than about three arcminutes should be treated with caution.

In order to distinguish the contribution of each component to the FIR emission, we have analyzed IRAS addscan (SCANPI) results for AM 0327–285. The spiral galaxy is usually the stronger FIR emitter in most mixed pairs, as found by Xu & Sulentic (1991). However, in the pair AM 0327-285 the early–type dominates the FIR emission, with F(60μm) = 0.3 Jy, $L_{FIR}= 1.6\times10^9 L_\odot$ detected at the position of the early–type. The dominance of the early–type galaxy may be seen from Fig. 6 in which the IRAS source is centered on its in–scan position (offset=0) and offset from that of the spiral by 0.3 arcminutes, well beyond the positional uncertainties in scan reconstruction. The key point is that, while the diffraction limit of the IRAS 60-cm aperture at 60μ is large compared to the galaxies (and their separation), the peak position of a detection is determined to a precision much better than the beam size - as witness the fact that positions from the Point-Source Catalog are often accurate to within 5 arcseconds. The far-infrared emission peaks closer to the early-type galaxy than to the spiral at about the 95% (3σ) confidence level.

Spiral galaxies in pairs (S+S) in general have $L_{FIR} > 2 \times 10^{11} L_\odot$ (Xu & Sulentic 1991) suggesting that the spiral galaxy in AM 0327–285 is underluminous. This could indicate

possible mass transfer from the spiral to the early–type galaxy with subsequent star formation or heating by another source.

3. Stellar population analysis

The strongest evidence for a recent cross fuelling event would be the detection of a young stellar component in the early type member of AM 0327–285. We used the procedure for stellar population synthesis developed by Bica (1988) and Schmidt et al. (1989) to estimate the star-formation history of the nucleus of the elliptical galaxy. The method uses a template library of star clusters, and estimates the chemical evolution in a test population with only two parameters: age and metallicity; no assumptions on gravity or details of stellar evolution are necessary, and the IMF is implicit in the cluster spectra. This assumes, of course, that the IMF in clusters and in interaction–induced bursts are similar. The procedure allows one to both determine the chemical enrichment and successive generations of star formation.

The method requires measurements of equivalent width for strong metallic lines over a wide spectral range (see Bica 1988 for more details). The metallic lines selected were the G band of CH (4301 Å), MgI + MgH (5175 Å) and CaII 8542, 8662 Å. These features were selected mainly because they a) are not disturbed by emission lines, b) are usually relatively strong and do not have complex behavior like the TiO bands, and c) have a comprehensively–modeled behavior as a function of the cluster age and metallicity (Bica & Alloin 1986, 1987). A wide variety of age–metallicity paths were tested and the one with the best χ^2 is shown in Table 1. We note that the code allows a single recent star-forming event, and in fact spectral decomposition is rather insensitive to multiple bursts of star formation.

This result indicates that the dominant population is old and metal–rich with $[Z/Z]_\odot=0.3$, while $\sim 10\%$ of the flux at 5870 Å arises from a young stellar population (age $\leq 5 \times 10^8$ yr), confirming that this early–type galaxy had recent star formation as suggested by photometry and far–IR data.

4. Discussion

Evidence for cross–fueling in early–type components of mixed pairs might take several forms: 1) the galaxy might appear bluer in optical colors due to direct light from young stars; 2) it might emit in the far–infrared (FIR) due to dust being heated by visible and ultraviolet light produced by recently formed stars, even if they are still heavily dust-shrouded; 3) a direct connection may be observed in some tracer of gas, such as optical emission lines; and 4) analysis of stellar absorption lines or population synthesis may reveal a young stellar population in the early–type galaxy. We consider each of these forms of evidence in this section.

We used spectroscopy, imaging, FIR, and stellar population synthesis to study the stellar content and history of star formation in the nuclear region of the early–type galaxy in the mixed pair AM 0327–285. The morphology of the early-type galaxy shows evidence that it has acquired stars, and perhaps gas, from
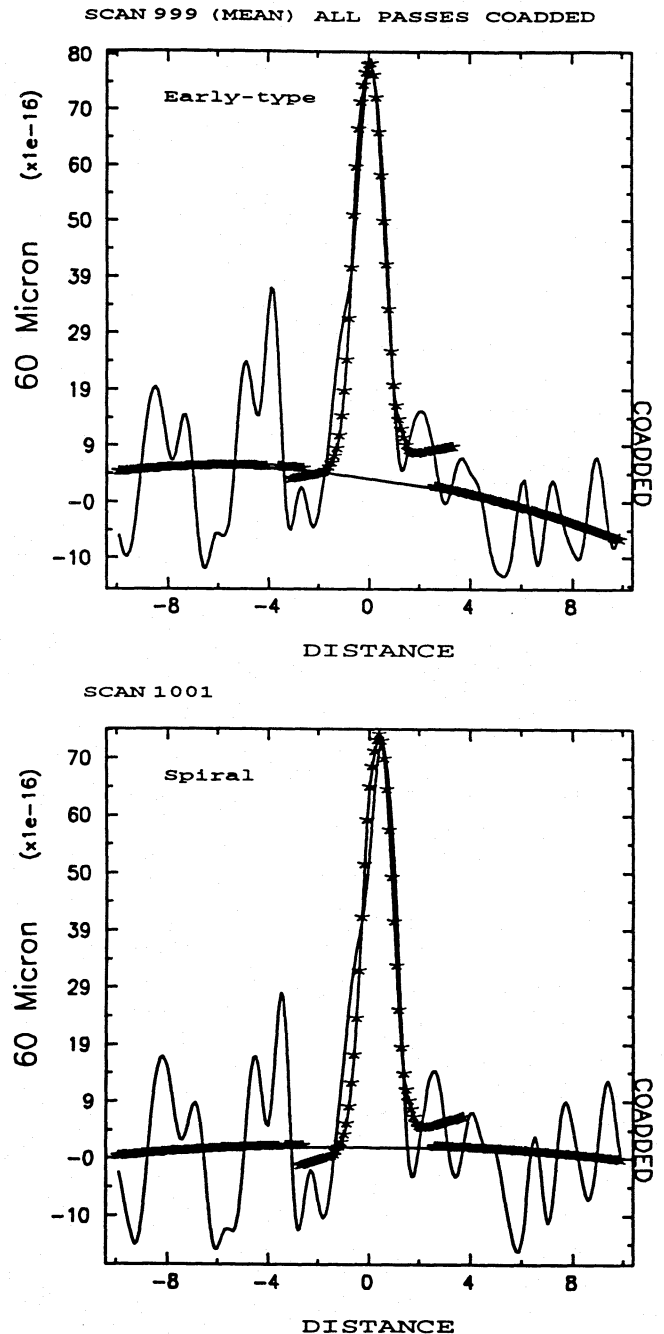

Fig. 6. Infrared addscan (60μm) centered on the early-type component (top) and on the spiral galaxy (bottom) of AM 0327–285. The horizontal axis gives the distance from the central position in arcmin along the IRAS scan direction. The vertical axis gives the flux detected. A point source template is fitted in each case. The early-type component matches the IRAS source in position much better than does the spiral, indicating that it dominates the 60μ flux

Table 1. Age and Metallicity distribution of AM 0327–28 E

		< 10	10	50	100	500	1000	5000	$> 10^4$
					AGE($\times 10^6$yr)				
metal rich	0.6								
	0.3	0	0.6	1.7	1.7	7.1	2.2	11.5	70.9
	0.0								3.4
$[Z/Z]_\odot$	-0.5								0
	-1.0								0
	-1.5								0
metal poor	-2.0								0

some dynamically cool system. It shows an unusual color gradient suggesting at least central star formation. The lack of reddening or extinction associated with the superimposed spiral arms indicates that the spiral lies behind the early-type galaxy. The spiral itself has strong grand–design structure implying a tidal origin (Elmegreen & Elmegreen 1987); a "bridge" arm certainly extends as far as the companion, though careful analysis of the images (see Fig. 3) shows that this arm does not physically connect the to the nucleus..

We found evidence for past cross–fueling in the form of a young stellar population component. There is evidence for on–going cross fuelling in the form of a quasi-continuous stream of emission-line gas between the S and E components. As discussed below, this stream is *not* identical with what appears to be a spiral feature connecting the two galaxies; on detailed examination the superposed spiral arm turns eastward well before crossing the nucleus of the early-type galaxy. Such a gas flow is in agreement with what Sotnikova (1991) predicted for mixed pairs. If $0.1 M_\odot$yr^{-1} is accreted in a mixed pair, in 10^8 years the early–type galaxy would have gas enough to have produced the young stars which have been detected with the stellar synthesis. Presence of line emitting in the spectrum may be residual gas transferred which shows that the cross–fueling is still active or that the efficiency of star formation is not very high in this case since a typical gas comsumption time scale in interacting galaxies is of the order of 10^8 years or less (Young et al. 1986). The dominance of the early–type galaxy in the FIR emission also supports the hypothesis of mass transfer. We stress that the mass transfer responsible for the star formation would have occurred several times 10^8 years before our present view, rather than being mediated by the structure and relative geometry of the galaxies as we observe them now.

For a better understanding of what past interactions have influenced the galaxies in this pair, we compared the morphology of the spiral to the simulation survey by Howard et al. (1993). Particularly noteworthy is the arm shape revealed most clearly in the model-subtracted image, but also visible in the original data. The western arm which at first appears to sweep into the early–type companion in fact curves eastward near the companion nucleus and continues faintly around the northern side of the spiral, so that there are two nearly parallel arms on this side and none ending to the south. This is a characteristic feature of the "ocular" galaxies discussed by, for example, Elmegreen et al. (1991). In agreement with their findings, the best fit from the Howard et al. simulations is for a relatively high–inclination direct orbit for the early–type galaxy, most likely in the range 45–60°. As in M51 (Howard et al. 1990; Salo et al. 1993), the two–armed spiral pattern was excited by a close passage some time ago, perhaps the companion's previous disk-plane crossing. The best time match is for about one disk–edge rotation (measured in the outer part of the spiral pattern) after closest approach. Taking a Hubble constant of 75 km s^{-1} Mpc^{-1}, the relevant period is about 3×10^8 yr. If the material now forming a remnant disk in the early–type companion was acquired from the spiral, the most likely time was about 3×10^8 yr ago.

A second timescale can be estimated from the shell–like structure NE of the early–type galaxy. If this represents material which has fallen through the core and turned around once, but not yet for the second time on the opposite side, limits on its age may be set if a characteristic velocity is adopted. Since both galaxies have similar luminosity (and, we assume, mass), and typical rotation and orbital velocities in similar pairs of galaxies are quite comparable, we take 250 km s^{-1} as the typical velocity. This material has then travelled more than 25 but less than about 60 kpc after passing through the core, for a dynamical age $1 - 2.4 \times 10^8$ yr (depending on how much acceleration took place while crossing the core). Both timescales for the accretion of this cold material are consistent, and also in agreement with the age of young stars found spectroscopically in the nucleus of the early–type component. We thus find support for the notion that star formation was indeed coincident with new gas–rich material entering this galaxy. It is more difficult to say whether this material in fact came from the spiral or a small gas-rich companion, though the timescale coincidence with the inferred closest approach to the spiral favors it as the origin of the material, by economy of hypotheses.

This pair exemplifies both the promise and some of the inherent ambiguities in analysis of single mixed-morphology pairs. Current surveys of large samples of these pairs should show how common young stellar populations and other evidence of recent mass transfer really are.

ments, particularly on interpreting the morphology of the spiral component in AM 0327-285. Extragalactic studies at the University of Alabama are supported by NSF/ State of Alabama EPSCoR Grant EHR–9108761.

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