Optical distortion of M86; star formation from cooling gas?

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Summary. Malin has produced a very deep photograph of M86 in which the outer isophotes of the galaxy are distorted. We show that the distortion is consistent with the presence of two regions of excess emission from M86 with a total luminosity in excess of $\sim 10^8 L_{\odot}$. The unusual X-ray morphology of M86 has been interpreted as evidence that this galaxy contains a hot corona which is being stripped by ram pressure. The excess optical emission is associated with features in the X-ray emission from M86, and we propose that the best model for it is as star formation due to cooling in the hot gas that is being stripped. Other models are discussed briefly. If the excess emission is due to star formation then it occurs under conditions very similar to those of a cooling flow, but offset from the centre of the galaxy. Thus M86 may provide a unique opportunity to investigate star formation in a cooling flow environment.

1 Introduction

M86 (NGC 4406) is one of the largest elliptical galaxies in the Virgo cluster. It is distinguished by an unusual X-ray morphology (Forman et al. 1979) and a large velocity relative to the Virgo cluster mean ($\sim 1500$ km s$^{-1}$). On the basis of these properties Forman et al. (1979) and Fabian, Schwarz & Forman (1980) have suggested that the hot ($T = 10^7$ K) interstellar medium in M86 is being stripped by ram pressure as the galaxy ploughs through the core of the Virgo cluster. They proposed that M86 accumulates the gas lost from its stars, while it is away from the centre of the Virgo cluster in its very long orbit, and that the gas is periodically stripped as the galaxy falls through the core of the cluster. This general picture is supported by the results of numerical simulations (Takeda, Nulsen & Fabian 1984).

Malin has developed new techniques for enhancing features of low surface brightness in astronomical photographs. One of his images, a deep print of the area around M86 in the Virgo cluster (Malin 1981), clearly shows the very large size of the envelope of this galaxy. Fabian (private communication) has suggested that the outer isophotes of M86 in this image are distorted. Here we investigate the distortion using a copy of the negative provided by D. F. Malin.
In Section 2 we demonstrate that the distortion of the outer isophotes of M86 is consistent with the presence of two blobs of excess optical emission. In Section 3 we estimate the luminosity of these blobs. They are found to coincide with features in the X-ray emission from M86, and in Section 4 we discuss what they might be. The magnitude of the excess and its association with the X-ray emission are best understood as stars forming from the cooling hot gas around M86. This offers the possibility of determining the properties of stars forming in an environment which strongly resembles a cooling flow (Fabian, Nulsen & Canizares 1984). It would also provide the most direct evidence to date that stars do form in the isolated cooling flows seen around many elliptical galaxies (Thomas et al. 1986).

2 Analysis of the image of M86

The image used was a negative prepared by D. F. Malin (1981). It is the photographic sum of high-contrast copies of three UK Schmidt plates of the area around M86, taken on IIIa–J emulsion through GG395 filters. This was scanned using the Mt Stromlo and Siding Spring Observatories PDS microdensitometer through a 125 μm square aperture with a scanning pitch of 80 μm and summed into 2 × 2 bins. The pixel size in the resulting digitized image is 3.73 arcsec square.

Plate 1 shows a false-contoured reproduction of the area around M86. The centre of the photograph is heavily saturated. Outside this the innermost contours are reasonably elliptical in shape but show increasing deviations from ellipticity away from the centre of the galaxy. Some of the ellipses best fitting the isophotes in this image are shown overlaid on Plate 1. One interpretation of the form of the deviation from ellipticity is that there is excess emission in areas NNW and east of the centre of M86.

To investigate this further a best-fitting ‘elliptical galaxy’ was subtracted from the image of M86. The galaxy was modelled with a fitting function \( f(u) \), which was a fifth-order polynomial in the squared elliptical radius, \( u \), defined by

\[
u(i, j) = (i-x_0)^2 + 2b(i-x_0)(j-y_0) + c(j-y_0)^2
\]

at the pixel \((i, j)\). The eccentricities, orientations and centres of the ellipses determined by \( u = \text{constant} \) were all allowed to vary smoothly with radius by making each of the parameters \( b, c, x_0 \) and \( y_0 \) quadratic functions of \( u \). This complicates the fitting procedure by making the definition of \( u \) recursive. However, no substantial problems were encountered because the ellipse parameters only vary slowly with radius. The elliptical galaxy so modelled has exactly elliptical isophotes which may change in eccentricity, twist and translate as a function of radius. Note that modelling the image of M86 simply as a polynomial in \( u \) is adequate in the present case because the heavily saturated image is very flat over a large area about the centre of the galaxy.

The model was fitted by minimizing the squared residual

\[
R = \sum_{i,j} (y_{i,j} - f[u(i,j)])^2,
\]

where \( y_{i,j} \) is the photographic density at the pixel \((i, j)\). The fit was made to the area of the image inside an ellipse, fitted to an outer isophote of M86, with principal axes of 331 × 216 pixels (20.6 × 13.4 arcmin; see Plate 2). After the initial fit it was found that a significant fraction of the residual was due to a number of compact images over the galaxy. To test the possibility that these might be significantly affecting the fit they were ‘patched’ from the image. (Patching involves removing a small area from the image and replacing it with pseudo-data which have the same mean, slope and noise as the pixels bordering those removed.) The patched residual image was then added back to the model and the fit repeated. The patching reduced \( R \) by over a factor of 2, but did not significantly affect the large-scale appearance of the residual image.
Plate 1. False-contoured image of M86. The digitized image of M86 is shown displayed using a false-contouring colour table to illustrate the shapes of the isophotes. Three ellipses which were fitted to isophotes are shown overlaid to highlight deviations from ellipticity. The innermost ellipse fits its isophote quite well, but further out the galaxy shows bulges to the east and NNW of its centre (north is up and east to the left). Note that the isophotes around M84 at the right of the plate are regular in shape. Note also the large saturated area at the centre of the galaxy. The print covers an area of $32 \times 29$ arcmin.
Plate 2. The residual image of M86. This plate shows the residual image of the area around M86 after subtraction of the best-fitting galaxy model (see text). The featureless area near the centre is where the photograph was saturated. X-ray contours from Forman et al. (1985) are shown overlaid. Regions of substantial excess in the residual image are visible to the NNW and east of the centre of the galaxy (north is up and east to the left). Note that the excess emission to the NNW coincides with the off-centre peak in the X-ray emission, while that to the east falls under a prominent ridge in the X-ray emission. The principal axes of the elliptical border are 20.6 × 13.4 arcmin.
Plate 2 shows the residuals after the best-fitting model has been subtracted from the image of M86. Excess emission to the east is clearly visible and is surrounded by an area where the image has been over-subtracted due to the effect of the excess in the fit. The area of excess emission to the NNW, though apparent, is less clearly defined. Part of it appears to have been lost due to the saturation of the central image. It is also less distinct because it lies close to the major axis. No prejudice as to the nature of the deviation from ellipticity has been introduced into the fitting procedure and, since both regions of excess lie to the NE of the major axis, the positions of the isophotes in the model have been biased this way. This has left excess emission along all of the SW side of the major axis (and a deficit between the two regions of excess emission to the NE of the major axis). The excess emission to the NNW has also caused over-subtraction on the saturated part of the image between it and the centre of the galaxy. We can draw no conclusions here about the existence or absence of excess emission in the saturated part of the image. Contours of the X-ray emission from M86 have been overlaid on Plate 2.

3 Quantifying the excess emission

Even with the assumption that the underlying galaxy is elliptical, it is not possible to identify regions of deviation from ellipticity without further subjective assumptions. The residual image in Plate 2 shows that our assumption, that there are two patches of excess emission in M86 which cause the distortion of the isophotes, is reasonable. In order to estimate the luminosity in these two patches we have taken the excess in the calibrated image of M86 over the best-fitting model discussed above. This underestimates the excess because the best-fitting model is biased above the underlying galaxy in the regions of the excess. This problem is worst in the NNW region where the excess emission is more diffuse. The image with compact sources removed was used for taking the excess and for photometric calibration.

The photometry of King (1978) was used to calibrate the surface brightness. King's definition of the radius, $r$, of an elliptical isophote, the radius at 45° to the principal axes, is related to the squared elliptical radius, $u$, by

$$u = \frac{1}{2}(1 + c) r^2,$$

(3)

in the notation of equation (1). The image data were binned into 100 elliptical annuli equally spaced in $r$, and the mean photographic density and mean $u$ computed for each annulus. The mean $u$ value was then used to compute a radius from equation (3) and this used to associate a surface brightness with the mean photographic density. Surface brightnesses were deduced by linear interpolation in log $r$ on the magnitudes given by King.

This calibration procedure assumes that the excess emission has the same colour as the underlying galaxy, since King's photometry was done in $B$ which differs from the effective pass-band of IIIa–J plus GG395 filter. The pass-bands are not greatly different, however, and other errors in estimating the excess (especially in the subtraction of the underlying galaxy) will dominate, unless for example the excess is due solely to line emission.

The calibration was used to assign a surface brightness to each pixel in the image and in the model. The difference between these (in intensity units) was then summed over the areas of the excesses and the results converted into $B$ magnitudes. The excess in a circle of radius 3.1 arcmin centred in the NNW region was 17.4 mag, while that in a circle of 2.5 arcmin radius centred in the east region was 16.6 mag.

The mean surface brightness of the excess emission is very small (30.0 and 28.6 mag arcsec$^2$, respectively – the peak surface brightness in the NNW region is comparable to that in the east). Despite this, the photograph of M86 which was used is sufficiently uniform that there is little doubt about the reality of the distortion in the isophotes. (Compare the image of M86 in Plate 1.)
The dominant source of error in assigning luminosities to the excess emission come from subtracting the underlying galaxy. This is difficult to quantify, but may be as much as a factor of 2 in the NNW region. As already noted, subtracting the best-fitting galaxy model tends to underestimate the excess. Since part of the excess has also probably been lost due to saturation in the NNW, it may be underestimated by a further factor of up to $\sim 2$.

Adopting a distance modulus of 30.8 for M86 (Hanes 1982), the absolute magnitude of the NNW excess is $-13.1$ mag, while that for the east excess is $-14.2$ mag. These correspond to $2.7 \times 10^7$ and $7.4 \times 10^7 L_\odot$, respectively in $B$.

4 Origin of the excess emission

Analysis of the image of M86 alone provides few clues as to the source of the excess optical emission. The most notable feature of the excess emission is its correlation with the X-ray emission from M86 (Plate 2). NNW of the centre of M86 the excess coincides with a prominent off-centre peak in the X-ray emission. This has been attributed to a ‘blob’ of gas being pushed from M86 by ram pressure (Fabian et al. 1980; Takeda et al. 1984). The excess emission to the east does not have such a striking counterpart, but does seem to be associated with another prominent ridge in the X-ray emission. Some of the structure in the X-ray emission to the south and east of M86 is probably caused by the halo of M87 extending into the field of view (Forman et al. 1979). The excess optical emission is associated with the most prominent irregularities in the X-ray structure close to M86.

If we assume that it is connected with the X-ray emission, then there are several possible causes for the optical emission. Based on the analysis of Forman, Jones & Tucker (1985), the cooling time of the X-ray emitting gas varies from about $1.5 \times 10^8$ yr at the centre of M86 to $5 \times 10^7$ yr at 30 kpc from the centre. (Values have been corrected for the different Virgo distance we are using, giving a central electron density $\sim 0.02 \, \text{cm}^{-3}$.) This is sufficiently short that some of the gas is very likely to be cooling to low temperatures at present. In fact, much of the hot gas around M86 was probably involved in a cooling flow before it started to be stripped (Fabian et al. 1984). A large part of the steady cooling flow will have been disrupted by the stripping and has not had time to become fully re-established. Despite this, the analysis of Thomas et al. (1986) gives an indication of the current gas cooling rate in M86 of about $0.5\text{--}1 \, M_\odot \, \text{yr}^{-1}$ (the gas plume was eliminated from this analysis). White & Chevalier (1984) have also proposed a cooling flow model for M86. The rate of cooling will have been enhanced by the compression due to ram pressure (and to a lesser extent by that due to the static pressure) as the galaxy encountered the Virgo intergalactic medium. The excess emission may then be due to either line emission or newly formed stars in the cooling gas.

In order that sufficient gas to account for the X-ray emission could be accumulated from stellar mass loss in M86 during its orbit, Fabian et al. (1980) suggested that the gas needs to have been hot enough not to have cooled significantly for the $\sim 5 \times 10^9$ yr during which the galaxy was away from the centre of the Virgo cluster. However, the extent and quantity of this gas is not significantly different from that around many similar galaxies, where it has also been attributed to stellar mass loss (Forman et al. 1985). The origin of the gas is likely to be the same in the present case. We note that the simple, self-contained cooling flow model for M86 does not account for the large quantity of gas it contains (White & Chevalier 1984; Thomas et al. 1986).

Line emission has been shown to be widely associated with cooling hot gas in both clusters (Fabian et al., and references therein; Hu, Cowie & Wang 1985; Johnstone, Fabian & Nulsen 1986) and elliptical galaxies (Phillips et al. 1986). Although the method we have used to determine the luminosity of the excess emission is not accurate if the excess is due to line radiation (Section 3), it cannot result in a gross underestimate of the line luminosity. The total optical luminosity
could not therefore be much less than $10^{41}$ erg s$^{-1}$ if it is due to lines. This is comparable to the total X-ray luminosity of M86 and rules out all the likely mechanisms by which the thermal energy of the hot gas could supply the energy for line radiation. This is in contrast to the situation in most cooling flows (Cowie, Fabian & Nulsen 1980; Cowie et al. 1983).

Johnstone et al. (1987) find a good correlation between the strength of H$\beta$ emission and that of the 4000 Å break in cooling flow galaxies in clusters. They explain this as due to a few per cent of the cooling gas forming into stars with an initial mass function resembling that for the solar neighbourhood. The line emission is powered by photoionization caused by the hot young stars. The fraction of the cooling gas involved in such star formation varies widely from one cluster to another. If a significant fraction of the cooling gas in M86 was forming stars with a solar neighbourhood initial mass function then the excess emission there could be line emission. This would require a short-lived (<10$^8$ yr) burst of star formation, since otherwise continuum emission from the accumulated stars would dominate. We cannot rule out line emission on observational grounds, however, because the emission is diffuse and lies away from the centre of the galaxy so that it could have been missed.

It is easier to make a case that the excess emission is due to newly formed stars. It has been noted many times that the most likely fate of cooled hot gas is in forming stars, but that in cooling flows these must have a non-standard initial mass function (Fabian, Nulsen & Canizares 1982; Sarazin & O’Connell 1983). The mass of hot gas in the inner regions of M86 has been estimated as few $\times 10^9 M_\odot$ (Fabian et al. 1980). If we assume that the mass-to-light ratio of the stars forming from the cooling gas is about 1, then only a few per cent of the gas need have formed into stars during the past $10^8$ yr to account for the excess emission. The stars causing the excess are coherent, but will separate from the gas blobs on their orbits in about one free-fall time, so that they must have formed in less than about that time. (The gas blobs are accelerated slowly from the galaxy, at speeds comparable to the line-of-sight velocity dispersion of the galaxy – see Takeda et al. 1984.)

In view of the cooling times quoted above, it is reasonable to expect that a few per cent of the hot gas has cooled in thermally unstable clumps during the past $10^8$ yr. Within the uncertainties, the required star formation rate is reasonably consistent with that determined by Thomas et al. (1986). We must assume, as in cooling flows generally, that the efficiency of star formation is high (Fabian et al. 1982; Sarazin & O’Connell 1983). The thermal instability will have distributed the stars widely, but with greatest concentration where the gas is densest (Nulsen 1986), so making the densest gas blobs visible. The assumption then, is that we are seeing the stars forming inside two blobs of gas as they are being pushed out of M86. Compression of the interstellar gas as M86 fell into the core of Virgo probably enhanced the rate of star formation.

In a normal cooling flow the hot gas is distributed symmetrically about the galaxy, so that thermal instability causes formation of stars that are also symmetrically distributed (at least on average). The light from these stars is very difficult to separate from that of the underlying galaxy because it is distributed in a similar fashion. This is aggravated if, as has been argued, the colours of the new stars differ little from those of the older stellar population (Fabian et al. 1982; Sarazin & O’Connell 1983). If the excess emission in M86 is due to stars newly formed from the cooling gas then this system gives us our first opportunity to directly measure the colours of the newly formed stars.

It is interesting to note that, from the computations of Hernquist & Quinn (1985), the stars forming inside the blobs will behave like a small stellar system merging with M86, forming into shells over the next few orbital periods. The shells will, however, be weak as their total luminosity is small relative to shell systems observed in many isolated elliptical galaxies (Carter, Allen & Malin 1982).

There are other possible explanations for the excess emission from M86 which involve stars,
but which discount the association between the excess and the X-ray emission. Perhaps the most prosaic is that we are seeing two low surface brightness dwarf galaxies. There is a small galaxy lying about 6 kpc NE of the centre of M86 visible in POSS prints, however, the required objects must be fainter and more diffuse than it. (This galaxy can just be seen at the edge of the saturated part of the image in Plate 2.) Even allowing for understimation of the brightness of the excess, the dwarf galaxies would be more diffuse than any seen previously (e.g. Binggeli, Sandage & Tamman 1985).

Alternatively, we could be seeing tidal disturbance or tidal debris in M86. We note that the X-ray morphology of M86 cannot be accounted for by tidal disruption if the X-ray plume is due to gas that arose in M86 (or another typical elliptical galaxy). The high density of the gas in the plume, and the fact that its pressure must be less than that for the gas remaining in M86, imply that this gas arises from well inside the optical envelope of M86. In fact, it must have arisen from roughly within the radius of the innermost common X-ray isophote, or about 2 arcmin of the centre of M86. It is not possible to tidally strip gas without also removing the associate stars from a galaxy. The failing of a tidal model for the gas plume is therefore that the ratio of X-ray to optical luminosities in the plume should be about the same as that at 2 arcmin from the centre of M86. The excess optical emission is orders of magnitude less than required for that case.

We therefore consider tidal models for the optical excess which make no association between it and the X-ray structure of M86. A tidal disturber would need to be small, r<10 kpc, to produce such small-scale features, and the disturbance would need to have happened recently so that it is still visible. At its speed relative to the Virgo cluster, M86 will have travelled about 150 kpc during the past 10^8 yr. This could have carried it past a number of candidate galaxies. At such a great velocity the disturber would also need to have been quite compact to have applied sufficient impulse to the stars of M86. For example, a galaxy for which GM/R= (100 km s^{-1})^2 would have caused a velocity disturbance of ≈13 km s^{-1} over a range comparable to its size, less than a 4 per cent kinetic energy perturbation to the stars involved (σ=260 km s^{-1}; Faber & Jackson 1976). It is not clear whether the form of the excess could be explained by a tidal disturbance or as tidal debris, but numerical simulations are needed to resolve this. Photometry may help with this question, since a tidal disturbance should have the same colour as the underlying galaxy.

5 Discussion and conclusions

The outer isophotes of M86 show significant deviations from ellipticity, consistent with the presence of two blobs of excess optical emission lying over that galaxy. The excess emission is brighter than about 16.2 mag in B, corresponding to about 10^{42} erg s^{-1} of optical luminosity. Further photometry and spectroscopy are required in order to discriminate between various possible sources for the optical excess. The excess is, however, associated with features in the X-ray emission from M86 and, on the basis of this, is best modelled as star formation within the cooling hot gas that gives rise to the X-ray emission from M86 (Forman et al. 1979; Fabian et al. 1980).

In the model put forward by Fabian et al. (1980) to explain the X-ray morphology of M86, its gaseous corona is not part of a cooling flow. Nevertheless, even the mean cooling time in the denser parts of the gas is comparable to or shorter than the time-scale on which the gas has been compressed in falling into the Virgo core. This means that conditions within the gas are not substantially different from those within a normal cooling flow (Fabian et al. 1984). It is therefore reasonable to expect that star formation is occurring in cooling hot gas in a fashion similar to a cooling flow. Because the dense gas blobs lie away from the centre of M86, they provide a unique opportunity to observe the process of star formation in a cooling flow environment.
Star formation from cooling gas

The haloes of hot gas around elliptical galaxies are probably produced by stellar mass loss, and the cooling time of the gas in them is generally short enough that some of it will be cooling to low temperatures at present (Forman et al. 1985; Trinchieri & Fabbiano 1985; Thomas et al. 1986). We therefore expect that only those galaxies which are kept stripped will not have substantial X-ray coronae. Since the gas is cooling, systems like M86, where a cooling hot corona is being stripped by ram pressure, should occur wherever large elliptical galaxies fall through X-ray clusters on elongated orbits (see Takeda et al. 1984). If the optical excess in M86 is due to star formation in the cooling gas then such excesses should be universally associated with the X-ray emission in these systems.

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References