Jets and the emission-line spiral structure in IRAS 04210+0400

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Abstract

We examine models in which jets are responsible for the formation of the emission-line spiral structure in IRAS 04210+0400. The kiloparsec-scale radio lobes in this active galaxy appear to be related to its extended emission-line spiral structure. The radio structure consists mainly of extended symmetrically bent, FR I-type lobes, which follow the emission-line spiral structure at their inner edge. In the central region of the galaxy a double radio source is observed with a separation of approximately 1 arcsec between its components, which are extremely well aligned with the hotspot from which the southern lobe expands outwards. Hill et al. (1988) suggested a model for the emission-line spiral structure invoking compressed interstellar matter, which is dragged away from the original jet path by the rotating ambient medium. From consideration of the propagation speed of the jets and the transverse ram pressure exerted by the rotating environment, we exclude this scenario as a possible origin of the spiral structure. We favour a model in which the jets themselves are bent by the rotating interstellar medium and possibly follows the emission-line spiral arms. We present fits of the model to the observed optical spiral structure. High sensitivity radio observations will be required to decide on the nature of the peculiar spiral structure in IRAS 04210+0400.

Key words: Galaxies: active - Galaxies: jets - Galaxies: individual: IRAS 04210+0400 - Galaxies: kinematics and dynamics - Galaxies: peculiar - Galaxies: Seyfert

1 Introduction

The nature of the spiral structure of disk galaxies has been a widely discussed issue in extragalactic astronomy since their discovery. Several mechanisms have been put forward in explanation, but to date no general consensus has been reached about a single process responsible for the spiral structure of galaxies. The most successful theories employ density waves (Lin & Shu, 1964) or galaxy interactions to produce the spiral arms (e.g. Toomre & Toomre, 1972). Another possibility is stochastic self propagating star formation considered by Gerola and Seiden (1978). Most probably, different mechanisms are at work in different galaxies, and these theories are complementary rather than competing.
On occasion, ejection phenomena have been suggested to be responsible for spiral arms in galaxies which did not fit into the conventional schemes. Van der Kruit et al. (1972) suggested that the anomalous radio and emission-line arms in NGC 4258 originated from an essentially instantaneous ejection of radio-emitting material from the centre of the galaxy in opposite directions. In their model, the observed radio arms are a transient phenomenon and represent the current position of these plasmons, which were ejected with a wide range of speeds. The trajectories of the individual parcels is determined by gravitational forces and ram pressure. Later on, several other similar models for the jets in NGC 4258 have been suggested which are consistent with the observation that the anomalous arms are bent in the same direction as the trailing spiral arms (e.g. Martin et al., 1989, and references therein).

Wilson & Ulvestad (1982) described a steady state model in which a two-sided jet propagates roughly in the rotational plane of a galaxy. The jet is then bent by the ram pressure exerted transverse to the jet by the rotating interstellar medium. They applied this model to the S-shaped radio structures found on a sub-kpc scale in the Seyfert galaxies NGC 1068, NGC 4151, and the radio galaxy 3C 293. The result of this model are leading spiral structures in the galaxy. Other mechanisms to obtain S-shaped jet pairs are pressure gradients in the hot gaseous halo of elliptical galaxies (Smith & Norman 1981) and precession of the jets (e.g. Gower et al. 1982).

Imaging, both ground based (Hill et al. 1988; Steffen et al. 1996a, 1996b) and by the Hubble Space Telescope (HST; Capetti et al. 1996) suggests that the spiral structure of the peculiar active galaxy IRAS 04210+0400 is due to a narrow ridge of emission line filaments. Its redshift is 0.0462 and was classified as a Seyfert 2 (Beichman et al., 1985), but the classification has been questioned by Hill et al. (1988). It shows an unusually extended and complex radio structure for this type of galaxies, with a total power of $2.4 \cdot 10^{23}$ W Hz$^{-1}$ at 20 cm. It has extended radio lobes, which are related to the optical spiral arms. Based on their observations, Hill et al. (1988) first suggested that the spiral structure could be due to the remnant of the interaction of the jets with the ambient medium. In this scenario the emission line filaments are produced during the passage of the jet through the interstellar medium. It is then carried away from its original location by the rotation of the galaxy forming a spiral structure.

In the present paper we analyze the suggestion by Hill et al. (1988) that the spiral structure in IRAS 04210+0400 is due to the interaction of the jets with the ambient medium. In Section 2.2 we consider the model proposed by Hill et al. (1988). In Section 2.3 we analyze the model proposed by Wilson & Ulvestad (1982) for other Seyfert galaxies. Section 3 contains the discussion of our results and our conclusions are summarized in Section 4.
2 The models

2.1 Observational evidence

The main observational reasons for investigating a model which invokes the propagation of the jets through the ISM as the cause for the emission-line spiral structure in IRAS 04210+0400 (Hill et al. 1988, Holloway et al. 1996; Steffen et al. 1996a,b) are, in brief:

- The spiral structure is emission line dominated.
- Radio lobes continue the optical spiral structure.
- Radio hotspots and bifurcations of optical spiral arms coincide.
- The inner radio double source is aligned (to within 1 deg) with the initial southern hotspot.
- The jets themselves are as yet not detected.

These are very strong arguments for the spiral structure and the radio ejecta in IRAS 04210+0400 to be physically associated, rather than related by coincidence.

2.2 Straight jets

The first three of the crucial observations listed above could be explained by a bent jet following the spiral structure. However, the accurate alignment of the inner with the outer radio structure suggests that the jets are straight. Therefore, we first evaluate the case in which the jets remain unbent during their propagation through the galaxy.

During the passage of a supersonic jet through the interstellar medium (ISM) the bowshock in front of it sweeps up and compresses the gas in its path (e.g. Taylor et al. 1992). Eventually, after it has moved away from the bowshock, the gas is entrained by the jet or merges back into the environment. What is left in a stationary ambient medium are filaments of emission-line gas delineating the path of the jet through its environment. However, in a rotating galaxy the gas can be dragged away from its original position along an arc of length \( s(r) \) following the local motion of the ISM. This situation is illustrated in Figure 1, where the head of the jet has reached a distance \( r_1 \) since ejection from the centre of the galaxy.

The shape of the spiral arms depends on the rotation curve \( v_g(r) \) of the galaxy and on the advance speed \( v_{jh}(r) \) of the jet head in the ambient medium.

We assume circular orbits of the interstellar medium at a velocity \( v_g(r) \). The length \( s(r) \) of the arc over which the ionized gas is dragged is then given by

\[
s(r) = v_g(r) \int_{r}^{r_1} \frac{dr}{v_{jh}(r)}, \tag{1}
\]
where $r$ is the distance from the centre of the galaxy, and $r_1$ is the present distance of the jet head, which propagates at the local speed $v_{jh}(r)$ through the interstellar medium. Here and in the following, the subscript ‘1’ indicates the value of a quantity at the current position of the jet head $r = r_1$.

An important parameter of the spiral structure related to the advance speed $v_{jh}$ is the pitch $p$ of the spiral structure close to the jet head. It can be defined as

$$p_{(r_1)} = \tan \theta = \left( \frac{ds(r)}{dr} \right)|_{r_1}^{-1} = \frac{v_{jh}(r_1)}{v_g(r_1)},$$

(2)

where $\theta$ is the angle between the jet and the tangent on the spiral arm at the position of the jet head (see Figure 1). If the orientation of the galaxy with respect to the observer is known or projection effects can be neglected, then this is a measurable quantity. As was discussed in Holloway et al. (1996), IRAS 04210+0400 is seen roughly face-on and the jets probably propagate close to the plane of the sky, we shall therefore ignore projection effects. The observed pitch $p$ can therefore be used to estimate the advance speed $v_{jh}(r_1) \approx p v_g(r_1)$ at the position close to the hotspots (see below). Other parameters, like the shape of the rotation curve or a slow change of the jet velocity, have a strong influence only on the inner spiral structure. For the simple case of constant advance speed of the jet head $v_{jh}$, the arc-length $s(r)$ over which the ionized gas at distance $r$ moved around the centre of the galaxy (while the jet continued to propagate up to a distance $r_1$) is given by

$$s(r) = \frac{v_g(r)}{v_{jh}} (r_1 - r)$$

(3)

The advance speed depends mainly on the jet speed $v_j$ and the ratio $\eta$ of the densities of the external medium $\rho_x$ and the jet plasma $\rho_j$ and therefore varies according to the external conditions. For a highly supersonic non-relativistic jet, as we assume is the case for IRAS 04210+0400, ram pressure arguments lead to a simple approximate expression for the advance speed $v_{jh}$ of the jet in an ambient medium (e.g. Leahy 1991)

$$v_{jh} = \frac{v_j}{1 + \sqrt{\eta}}$$

(4)

To obtain the corresponding relativistic expression, $\eta$ is to be replaced by $\eta/\gamma^2$, where $\gamma$ is the Lorentz factor (after Martí et al. 1994). Hence, a relativistic jet mimics a heavy non-relativistic jet and the advance speed approaches the bulk jet speed $v_j$ as the latter approaches the speed of light. Equation 4 can be combined with Equation 1 to obtain the arc-length $s(r)$.

### 2.2.1 Evaluation

We now evaluate the applicability of this model to IRAS 04210+0400. The spiral structure in IRAS 04210+0400 can be roughly characterized by the pitch $p$ of
the spiral at the current position of the jet head. However, the exact position of the jet head is difficult to determine from the observations. In our model of a jet crossing a shocked interface between the interstellar and intergalactic medium, ISM and IGM, respectively (Holloway et al., 1996, Steffen et al., 1996c), it is to be expected that the expansion speed of the jet material is increased in the IGM. Therefore, a reasonable choice seems to be an ‘effective’ position of the jet head shortly beyond the beginning of the hotspot region. We estimate the pitch of the spiral in IRAS04210+0400 to be in the range 1.5-2.5 and adopt a value of $p = 2$. Knowledge of the exact value is not necessary for our analysis. It is only required that $p$ is of order unity.

Using Equations 1 & 4, the velocity of the jet $v_{j1}$ at the position of the jet head can be expressed in terms of the measurable quantity $p$ and the other parameters as follows

$$v_{j1} = p \cdot v_{g1} (1 + \sqrt{\eta_1}).$$

(5)

Extragalactic jets are expected to have very low densities compared to the ISM, though the range of values is not known. However, from the assumption of a straight jet in IRAS 04210+0400 (based on the alignment of the inner and outer radio structure) and the observed pitch $p$ of the spiral arms, we can estimate a lower limit for the density ratio $\eta$. The radius of curvature $R_j$ of this bending is approximately given by $R_j/h_j \approx \eta^{-1} v_j^2/v_g^2$, with $h_j$ representing the jet diameter. The jet speed is unknown. We therefore use Equation 5 to eliminate $v_j$ and $v_g$ introducing the observable pitch $p$ of the spiral arms. We find that

$$\eta = \left( \frac{R_j}{p^2 h_j} - 1 \right)^{-2}$$

(6)

at the position of the jet head. From the distance $D = 4.5\text{arcsec}$ and size $d < 0.5\text{arcsec}$ of the hotspot and a conservative upper limit of the misalignment with the inner double source ($\alpha < 2\text{deg};$ Steffen et al. 1996b), we estimate that $R_j/h_j \approx D/(2d \sin \alpha) > 130$ and therefore find the density ratio between the ambient medium and the jet to be $\eta < 1/22$. From this analysis it is clear that the jet can get away without being bent by the rotating interstellar medium only if it is denser than the environment. This conclusion is drawn from the observations far from the centre of the galaxy. Closer in, at higher environmental density, the density contrast between the jet and the ambient medium is required to be even higher. The speed of a heavy jet is approximately the same as its advance velocity in the ISM. Hence, in this model, the jet velocity can only be roughly $v_j \approx p \cdot v_{g1} \approx 400\text{km s}^{-1}$ (using $v_{g1} = 200\text{km s}^{-1}$).

The high degree of collimation of the jet inferred from the small size of the hotspots, suggests that the jet is in approximate pressure equilibrium with the environment. Then the temperature ratio between the jet and the environment
is roughly the inverse of the density ratio, and we therefore infer a jet temperature of
\[ T_j \approx \eta \cdot T_{ISM} \ll T_{ISM}, \tag{7} \]
i.e. a very cold jet, possibly with properties similar to galactic jets.

Such a heavy ballistic jet would probably not flare at the interface between the interstellar and the intergalactic media. To explain these observations a collision of the jets with large dense clouds could be invoked (Higgins et al. 1996). However, the symmetry of the flaring of the two jets on either side, renders this possibility highly unlikely. From the previous considerations we conclude that the suggestion by Hill et al. (1988) that a pair of straight jets is the origin of the spiral structure in IRAS 04210+0400 is not a viable model.

\section*{2.3 Bent jets}

As an alternative, we now analyze a model of jets bent by ram pressure of the rotating interstellar medium as outlined by Wilson & Ulvestad (1982). All assumptions and limitations discussed in their paper also applies to IRAS 04210+0400. Their main assumptions are: constant jet speed, adiabatic expansion of the jet, and jet propagation in the plane of rotation of the galaxy. As discussed in the previous section, we shall neglect projection effects. The alignment of the inner double radio source with the southern hotspot is assumed not to represent the initial jet direction, as it was the case in the previous section.

Figure 2 shows a schematic representation of the geometry involved in this model. The steady state path of the jet can be found by numerically integrating the equation

\[ y'' = \frac{\rho_g(r) v_g^2(r)}{\rho_j h_0 v_j^2} \left[ \frac{\rho_g(r) v_g^2(r)}{\rho_j v_j^2(r)} \right]^{-1/2\Gamma} \cdot \left[ \frac{(y' y + x)^2}{x^2 + y^2} \right]^{(2\Gamma-1)/2\Gamma} \left[ 1 + y^2 \right]^{(\Gamma+1)/2\Gamma} \tag{8} \]

This is Equation (8) in Wilson & Ulvestad (1982). Here \( x \) and \( y \) are Cartesian coordinates, \( r \) is the distance from the galactic nucleus, \( \rho \) is the density and \( v \) is the velocity. Subscripts \( g \) and \( j \) refer to quantities of the galaxy and the jet, respectively. The effective radius of the jet is \( h \), \( r_0 \) denotes a small starting distance and \( \Gamma \) is the adiabatic index. Initial conditions for the numerical integration are \( y = r_0 \) and \( y' \gg 1 \) at \( x = 0 \).

An important ingredient in Equation 8 is the rotation curve of the galaxy, given by \( v_g(r) \). The rotation curve of IRAS 04210+0400 is unknown because of the disturbed line profiles and its face-on orientation with respect to the observer. We considered several representative rotation curves, which can be
described with the following equation (after Binney & Tremaine, 1987):

$$v_g(r) = \frac{r}{a} \frac{v_m}{\sqrt{1 + \left(\frac{\zeta}{a}\right)^2}}$$  (9)

where $a$ is a scale length and $\zeta$ a constant. As representative examples we choose a rotation curve with a fast transition from solid body rotation to constant velocity with $a = 0.15 \text{ kpc}$ and a slow transition with $a = 4.5 \text{ kpc}$ and $\zeta = 2$ in both cases. Choosing a rotation curve which is slightly rising or falling after the transition from solid body rotation does not make an appreciable difference.

Following Wilson & Ulvestad (1992) we assume that the density of the galactic ambient medium remains constant within $r < r_d$ and drops with the square of the distance further out. Using parameter values typical for spiral galaxies, in Figure 4 we compare some example trajectories obtained varying the density of the jet. The values used in the numerical calculations are given in Table 1. For each of the three examples, we varied the density of the jet in a range for which the ‘final’ direction of the jet (arbitrarily chosen at $r \approx 12 \text{ kpc}$) lays within the radio lobes.

The individual trajectories have been rotated such that they all pass through a suitable fitting point on the spiral structure. In the northern arm we chose the secondary maximum of emission at $r = 6 \text{ kpc}$ ($\text{PA}_n = 14 \text{ deg}$). In Figure 4 we compare the results with an [OIII]-5007Å image which shows the emission line spiral structure of IRAS 04210+0400 (Steffen et al. 1996c). In the frames 4(a) and 4(b) the calculated spirals are symmetric, using rotation curves ‘a’ and ‘b’, respectively. They have both been fitted to the northern arm and clearly expose the asymmetry of the spiral arms in IRAS04210+0400. In the southern arm the bending is initially stronger and seems to straighten out or even ‘bend back’ at $r \approx 5.5 \text{ kpc}$ (the point of strong spectral flaring; Holloway et al. 1996, Steffen et al. 1996c). However, the southern arm is brighter and smoother than the northern equivalent. This could be attributed to a higher galactic density in this region (rather than lower jet power, because of the stronger line emission). In Figure 4(c), we therefore show a specific fit to the southern arm (Case ‘c’) chosing the point of reference at $r = 4.4 \text{ kpc}$ and $\text{PA}_s = 166 \text{ deg}$ (the southern tip of the third contour from the absolute maximum), together with Case ‘b’ for the northern arm. Here only difference between the calculations for the norther and southern arm is an increase of the galactic density by 30% in the south, sufficient to obtain the required bending of the jet.

Note that none of these sets of parameters are unique. Similar results can be obtained varying the jet velocity or the density of the ambient medium. Note also that a similar result can be obtained by changing the density or rotation velocity of the galaxy, as well as the speed of the jet, since basically only the relative ram-pressure determines the magnitude of the bending. Shape of the rotation curve or the density variation as a function of distance do also influence the jet trajectory to some extent. Although we cannot determine unique values
of the basic parameters involved in the model, we can at least say that the bent jet model is consistent with the observations to within reasonable values of the parameters.

Within the framework of this model we can now predict where the underlying jet should point in the inner region of IRAS 04210+0400. We suggest that the northern and the southern radio jets should be oriented at position angles $\text{PA}_n \approx 45$ deg and $\text{PA}_s \approx 135$ deg with an estimated error of 10 deg, as given by the range of initial position angles listed in Table 1. Within the estimated error, these values are almost independent of the choice of parameters for the jet trajectory as long as it satisfactorily fits the spiral structure.

3 Discussion

We have examined two different candidate models for the formation of the emission-line spiral structure in IRAS 04210+0400 involving jets ejected from the galactic nucleus. We exclude the suggestion by Hill et al. (1988) of straight jets which interact with the ISM as a possible explanation for the observations. We find that a second model, considering jets bent by the rotating ambient medium is a better candidate.

Fitting this model to the optical spiral, we predict that the northern and the southern radio jets should be oriented along a line inclined by about 45 deg to the north-south axis, contrary to the position angle (6 deg) of the line joining of the inner radio components. High sensitivity radio observations will be required to detect the jets connecting the inner and outer radio structures and to clarify the nature of the central double source and its alignment with the southern hotspot.

We found that the initially stronger bending of the southern arm compared to the northern arm could be attributed to different densities in the interstellar medium. An asymmetric density distribution explains not only the initially stronger jet bending in the southern arm, but also the apparent difference in scale size in the two arms. In particular, the optical and radio features appear to be somewhat larger in the northern arm, suggesting a reduced resistance of the ISM to the action of the jet. The brightness of the extended northern radio emission is also lower than its southern counterpart (Steffen et al., 1996b), another pointer to a reduced interaction with the environment. If IRAS 04210+0400 is a disk galaxy, this effect could be due to a difference in the inclination angle between the jet and the disk, rather than an intrinsic asymmetry of the galactic disk (for a discussion of the classification of IRAS 04210+0400 see Holloway et al., 1996). However, because of the presence of a close companion galaxy, even an intrinsic asymmetry due to interaction cannot be excluded.

The model of a stationary jet bent by ram-pressure provides no direct explanation for the two strong radio components which are located within 1 arcsec.
of the centre of the galaxy. There are broad blue and red-shifted wings in the spectral lines which have a spatial separation similar to the radio components, suggesting that they are related (Holloway et al., 1996). The longslit spectroscopy and also the recent HST imaging (Capetti et al., 1996) shows that the inner kiloparsec-scale region is very clumpy. We therefore speculate that at least the northern one of the central radio components is caused by the interaction of the jet with a dense cloud, possibly temporarily cutting off the power supply to the regions further out. This would explain the reduced brightness of the northern arm (in the optical and the radio regime) and the northern gap in the emission-line intensity. Considering the parameters used in our calculations, we find that this can be achieved by a dense cloud with a diameter of a few tens parsecs following the galactic rotation at a distance of 1 kpc from the centre (assuming $v_{g}(1 \text{ kpc}) \approx 100 \text{ km s}^{-1}$). The size of the cloud scales with the rotation velocity.

In the present form, the bent jet model assumes that the emission line gas is located at the position of the jets. However, since it involves a stationary jet configuration, emission line gas could actually be dragged away from this path. Therefore, it should show a rather sharp edge on the upstream and a smoother or filamentary transition on the side downstream of the environmental gas flow around the jet.

At this time, we cannot exclude jet precession or interaction with the companion galaxy as origins for the spiral structure in IRAS 04210+0400. For further modeling knowledge about the rotation of the galaxy is vital, since the bent jet model predicts that the spiral arms are leading, as opposed the anomalous arms NGC 4258, which are trailing, excluding the stationary ram-pressure bending as a viable model for this galaxy. Martin et al. (1989) suggested that the jet and the tunnel created in the ISM follows the rotation of the galaxy and is therefore straight in the corotation zone, while it stays behind further out.

Detection of collimated jets connecting the inner and outer radio structure and measurement of the rotation curve of IRAS 04210+0400 would enable us to distinguish between models with straight jets (e.g. interaction with its companion or a jet following the corotation) and non-corotating precession or ram-pressure bending. Since the total radio power of the galaxy is only $2.4 \cdot 10^{23} \text{ W Hz}^{-1}$ at 20 cm, very high sensitivity will be required to detect the jets themselves. The observation of a displacement between bent radio jets and the emission-line spiral would indicate that the situation in reality was some combination between a bent-jet model and the model discussed in Section 2.2.

To discuss the interaction scenario for IRAS 04210+0400 in any detail, more spectroscopic information on the companion and a better spectroscopic coverage of IRAS 04210+0400 itself are needed. Deep imaging of the environment around IRAS 04210+0400 would be useful to search for traces of the interaction. Future work should also focus on the classification of the galaxy (disk or elliptical) and the rotation curve of this unique object.
4 Conclusions

We have evaluated two different candidate models for the formation of the emission-line spiral structure in IRAS 04210+0400 involving jets ejected from the galactic nucleus. We exclude the suggestion by Hill et al. (1988) of straight jets which interacted with the ISM as a possible explanation for the observations. We find that the second model of two jets bent by the rotating ambient medium is a better candidate. Fitting this model to the optical spiral, we predict that the northern and the southern radio jets should be oriented at position angles $\text{PA}_n \approx 45$ deg and $\text{PA}_s \approx 135$ deg with an estimated error of 10 deg. Detection of the jets on the intermediate scale between the inner and outer radio structures will be necessary to discriminate between the current models. High sensitivity radio observations will be required to search for the jets.

Acknowledgements

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References


Table 1: The jet and galaxy parameters for two different rotation curves (a,b) are given. For each rotation curve five different jet densities were considered. For rotation curve ‘b’ two separate sets (northern and southern arm, respectively) are given, which are distinguished by the density of the ambient medium. PA is the position angle of the initial jet direction measured in degrees. Parameters which are the same for all calculations are: \( r_d = 2.2 \) kpc, \( v_m = 200 \) km s\(^{-1}\), \( r_m = 10 \) kpc, \( r_j = 2 \) kpc, and \( h_0 = 3 \) pc. In the table distances are measured in kpc, velocities in 1000 km s\(^{-1}\), and densities in \( 10^{-23} \) g cm\(^{-3}\).

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Figure 1: Schematic view of the model with straight jets and a spiral produced by enhanced density material being dragged away from its original position by the rotating interstellar medium.
Figure 2: Schematic view of the model with jets bent by the rotating interstellar gas.
Figure 3: Rotation curves with a sharp and a slow rise have been considered.
Figure 4: The observed emission-line spiral structure (Steffen et al., 1996c) can be reproduced by a jet bent by the ram-pressure of the rotating interstellar medium in the galaxy. The curves in each panel show 5 jets with different densities. Frames ‘a’ and ‘b’ represent calculations for different rotation curves, whereas frame ‘c’ is for the same rotation curve as ‘b’, but with a higher ambient density in the southern spiral arm. The scale of 5 kpc marked on the frames corresponds to 4.5 arcsec (H$_0$ = 75 km s$^{-1}$ Mpc$^{-1}$).