Astron. Astrophys. 361, 888–894 (2000)

ASTRONOMY AND ASTROPHYSICS

Radio jet-blown neutral hydrogen supershells in spiral galaxies?

Gopal-Krishna[1] **and Judith A. Irwin**[2]

[1] National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune University Campus, Pune – 411007, India (krishna@ncra.tifr.res.in)
[2] Department of Physics, Queen's University, Kingston, K7L 3N6, Canada (irwin@astro.queensu.ca)

Received 21 April 2000 / Accepted 8 August 2000

Abstract. Taking a clue from the pair of HI supershells found in the Scd galaxy NGC 3556 (M 108), we propose a new mechanism for the origin of HI supershells in gas-rich massive galaxies. In this scenario, the two supershells were inflated out of the neutral hydrogen disk due to the localised flaring of a pair of radio lobes formed by the jets ejected from the nucleus during an active phase about $\sim 10^7$ years ago, but have faded away by now. It is shown that the salient features of this supershell pair, such as their symmetrical locations about the galactic centre, the anomalously large energy requirements, the large galactocentric distances, as well as the Z-symmetric hemispherical shapes, find a more natural explanation in terms of this scenario, as compared to the standard models which postulate either a massive starburst, or the infall of external gas clouds. Other possible implications of this hypothesis are briefly discussed.

Key words: galaxies: general – galaxies: ISM – galaxies: jets – galaxies: kinematics and dynamics – radio continuum: galaxies – radio lines: ISM

1. Introduction

An important manifestation of the activity inside the disks of gas-rich galaxies is their highly structured HI distribution, marked by cavities, shells and supershells. First discovered in the Milky Way (Heiles 1979, 1984), such features are now known to exist in a number of spiral galaxies (e.g. Lehnert & Heckman 1996, Irwin & Seaquist 1990, Puche et al. 1992, Brinks & Bajaja 1986). Exceptionally huge HI arcs and loops extending across several kiloparsecs have been identified with greater clarity in the HI images of a number of edge-on spirals, such as NGC 5775 (Irwin 1994), NGC 4631 (Rand & van der Hulst 1993), NGC 3044 (Lee & Irwin 1997, hereafter LI97) and NGC 3556 (M 108, King & Irwin 1997, hereafter KI97). These have been interpreted as expanding supershells because of a loop-like or circular appearance in projection and either a persistence over a wide velocity range or, in a few cases, as some evidence for expansion in position-velocity space. Two main classes of explanations for the supershells posit the source of their kinetic energy to be, respectively, internal and external to the parent galaxy.

The internal source model involves starbursts, driving stellar winds (or superwinds) and subsequent supernova explosions (e.g. Lehnert & Heckman 1996). The "chimney model" (Norman & Ikeuchi 1989), for example, attempts to explain disk-halo features and other halo gas via processes related to underlying star formation. The association between extraplanar Hα filaments and star forming regions in the disk of NGC 891 and other correlations between halo emission and in-disk tracers of star formation (Dahlem et al. 1995; Rand 1997) argue in favour of such models. If the presence of HI supershells is found to correlate with the existence of other halo gas, as might be expected in the chimney model, then stellar winds and supernovae are expected to be responsible for the HI supershells as well.

The main difficulty with the starburst model for HI supershells lies in the required input energies for the largest shells. Using standard assumptions that the expanding supershells are in the post-Sedov phase following an 'instantaneous' injection of energy (cf. Chevalier 1974), HI supershells often require energy input from staggering numbers of spatially correlated supernova events. This was realized early on for our own Galaxy (Heiles 1979, 1984). For external edge-on galaxies, since we are selectively observing only the largest shells, the energy deficit problem is exacerbated. In some cases, hundreds of thousands of clustered supernovae are required (e.g. KI97, LI97), a conclusion which is not changed significantly if the energy is injected continuously over the lifetime of the shells. Other evidence against star formation processes creating the HI shells is also emerging. Rhode et al. (1999) find no optical evidence for recent star formation in the numerous lower energy HI holes of Holmberg II and note that X-ray and FUV emission are also absent. They conclude that supernovae have not played a part in the formation of the HI shells. Efremov et al. (1998) outline numerous other examples in which there appears to be no relation between HI shells and star formation. They, as well as Loeb & Perna (1998), propose that the HI shells are produced, instead, by gamma ray bursts.

The alternative external source hypothesis invokes infall of massive gas clouds on to the galactic plane, as a result of grav-

Send offprint requests to: J.A. Irwin

itational interaction with neighbouring galaxies (see Tenorio-Tagle & Bodenheimer 1988). This resolves the energy problem since input energy is then a function of the mass and velocity of the infalling cloud. Evidence in favour of this hypothesis comes from observations of high velocity clouds (HVCs) around our own Milky Way and the signatures of interaction in M 101 (van der Hulst & Sancisi 1988) and NGC 4631 (Rand & Stone 1996). It does, however, require that the galaxy be in some way interacting with a companion or, at least, that sufficiently massive clouds be in the vicinity.

Recent observations are revealing galaxies which are apparently isolated, yet harbour extremely large HI supershells. Two striking examples are the nearby, SB(s)cd galaxy, NGC 3556 (KI97) and the SBc galaxy, NGC 3044 (LI97). Both of these galaxies exhibit radio continuum halos extending to $\sim\ 5$ kpc from the galactic plane and have a number of supershells requiring energies up to a few $\times\ 10^{56}$ ergs. These supershells are too large and energetic to have been produced by conventional clustered supernovae. At the same time, there appears to be no evidence for interaction or nearby companions, either.

We propose here a new explanation for HI supershells. That is, that they have been formed by radio jets which plow through the interstellar medium (ISM), accreting ISM gas and sometimes inflating bubbles. This allows for an internal energy source for the HI shells, provides a natural explanation for any spatial symmetries seen in the HI features, and also resolves the energy problem. In Sect. 2, we provide arguments in favour of jet inflated HI bubbles, Sect. 3 presents the model, and Sect. 4 discusses the implications of this scenario.

2. The case for a radio jet origin for HI supershells

2.1. Radio jets and AGN in spiral galaxies

Seyferts are one class of disk galaxy for which several examples of the nucleus ejecting a radio jet pair have been found (e.g. Ulvestad & Wilson 1984a, 1984b, Kukula et al. 1995, Aoki et al. 1999). Likewise, several cases of jets occurring in normal spiral galaxies have been reported (e.g. Hummel et al. 1983). Prominent examples include NGC 3079 (de Bruyn 1977), NGC 5548 (Ulvestad et al. 1999) and Circinus (Elmouttie et al. 1998).

The total energy output from such nuclear activity can approach 10^{60} erg, assuming that the nuclear activity lasts $\sim\ 10^7$ years, and arises from accretion onto a supermassive black hole of $10^8 M_\odot$ at 10% of the Eddington limit with the canonical 10% efficiency. In "normal" spiral galaxies, the central mass may be lower; for example, the bipolar outflow from the SAB(rs)cd galaxy, M 101 may be produced by a central $\sim 10^6$ $M_\odot$ black hole (Moody et al. 1995). While jets are not always observed directly, the growing number of supermassive black holes inferred to be present in the nuclei of normal disk galaxies (Kormendy & Richstone 1995, van der Marel 1999), including late-type disks (Ho et al. 1997), the Milky Way itself (e.g. Genzel et al. 1997) and gas-rich, large low-surface-brightness galaxies (Schombert 1998), lend weight to the idea that many such galaxies may have undergone phases of nuclear activity accompanied with a bi-directional ejection of relativistic plasma jets, before entering a dormant nuclear phase.

Recent studies have also revealed that the ejection of jets can take place at small angles to the large-scale galactic disk (e.g. Nagar & Wilson 1999; Kinney et al. 2000), plausibly leading to clear signatures of their dynamical interaction with the ISM. A classic case of such an interaction is the bow-shaped morphology of the radio lobe in the well known Seyfert galaxy, NGC 1068, which strongly suggests that the kiloparsec-scale radio jets are ploughing through the disk medium (Wilson & Ulvestad 1987, Axon et al. 1998). A dynamical interaction of the jets with the disk is also evident in the case of the spiral galaxy M 51 which is at the low end of nuclear activity scale. Here, the jets seem to have created a pair of 'radio lobes' on opposite sides of the nucleus; whereas one of the lobes is bow-shaped, the other one is actually resolved into a ring which is also detected in Hα emission (Ford et al. 1985). Another example is NGC 4258 whose VLBI jet has been ejected close to the galaxy disk (see Cecil et al. 1995, Herrnstein et al. 1997, Cecil et al. 1998). Large scale (14 kpc length) "anomalous arms" are also seen *within* the galactic disk and have been interpreted as manifestations of a larger-scale jet (e.g. Martin et al. 1989, but see Cox & Downes 1996). In M 101, the bipolar outflow is also roughly confined to the disk, with the outflow not expected to extend beyond a height of 400 pc (Moody et al. 1995). Additional support for the jet-disk interaction hypothesis in these disk galaxies comes from the detection of shock-excited optical emission lines associated with the radio lobes, as discussed in some of the references cited above.

2.2. Jet inflated bubbles in the lobes of radio galaxies

It is further interesting to note that radio bubbles and shells of synchrotron plasma have been discovered within the lobes of a few radio galaxies. Two spectacular examples are 3C310 (van Breugel & Fomalont, 1984) and Hercules A (Dreher & Feigelson 1984). In Hercules A, in addition, peculiar dark shells, about 3 kpc in size, have been found straddling the nucleus along the radio outflow axes (Baum et al. 1996). For the dark shells, Baum et al. prefer an explanation in terms of expanding bubbles of hot gas ejected from the active nucleus along the radio axis, in agreement with plasmon-like ejection from the core, though they do not rule out other possibilities.

These cases provide a clue that the radio bubbles/shells may have been 'puffed' up due to localized instabilities in the radio jets, occurring at distances of a few kiloparsecs from the active nucleus (e.g. Morrison & Sadun 1996). Should such instabilities arise also in the jets ejected within disk galaxies (Sect. 2.1), it is quite plausible that the resulting increase in pressure at those locations would inflate bubbles and shells out of the ambient ISM material which is HI rich, in the case of spirals. Such features, puffed out of the disk during the brief phase of jet instability, would remain visible past the radiative lifetime of the synchrotron plasma against the radiative and expansion losses, which is typically of order 10^6–10^7 years.

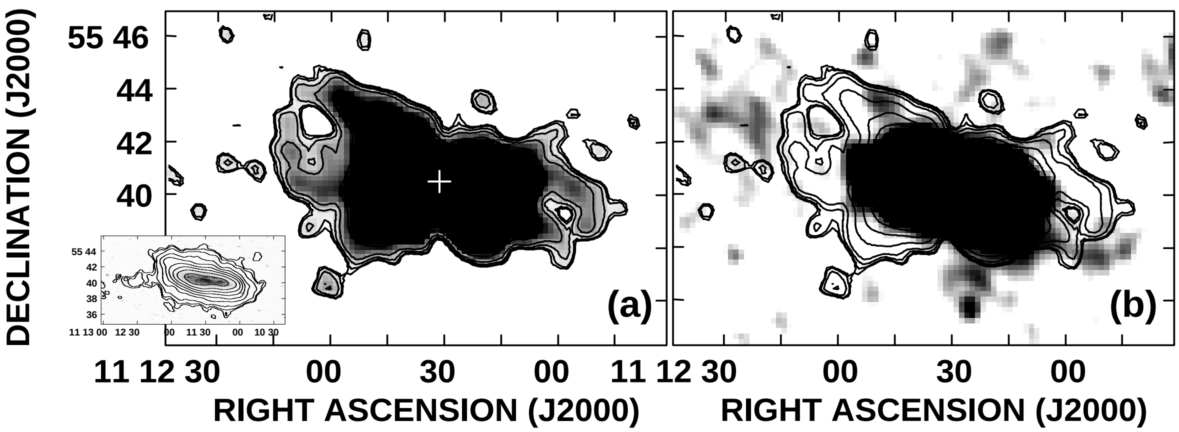

Fig. 1. a Superimposition of two channels of HI emission of NGC 3556 from KI97 at velocities 633 km s^{-1} (east side) and 757 km s^{-1} (west side). The greyscale is set to emphasize the HI loops on either side of the galaxy and ranges from 0.9 mJy beam^{-1} (2σ) to 3 mJy beam^{-1}. Contours are at 0.9, 1, 1.25, 1.7, and 3 mJy beam^{-1} and a white cross marks the galaxy's optical centre. **Inset.** Total intensity HI image of NGC 3556 (contours) from KI97 superimposed on an optical image of the galaxy. **b** HI contours as in (a) superimposed on a greyscale 20 cm continuum map (also from KI97) to emphasize the faint continuum features. The greyscale ranges from 0.23 mJy beam^{-1} (1σ) to 1 mJy beam^{-1}.

2.3. Candidate galaxies

2.3.1. NGC 3556

In NGC 3556, the two most prominent supershells are located symmetrically near the opposite extremities of the galaxy. KI97 have carried out a detailed mapping of the HI and radio continuum emission from this nearly edge-on galaxy located 11.6 Mpc away. The superimposition of 2 channels of HI emission, symmetrically placed in velocity about systemic, are shown in Fig. 1a. The most obvious features are two loops of HI, producing extensions to the east and west along the major axis. Fig. 1b shows the HI emission from these velocities superimposed on the radio continuum map, the latter taken from entirely independent observations. The abrupt density drop-off in the radio continuum map occurs roughly where the optical galaxy ends (Fig. 1a inset). The salient features of this system most relevant to the present study (see Fig. 1; KI97) are:

(a) Two symmetrically placed giant HI loops are seen originating at a projected galactocentric radius of about 12 kpc on the east and west major axis. They appear to originate right at the opposite edges of the optical disk and extend, not perpendicular to the disk plane, but rather parallel to it and outwards.
(b) The giant HI loops or supershells are slightly bent into a Z-symmetry.
(c) These HI loops are most obvious in velocity channels which are equally spaced about the systemic velocity of the galaxy (though they extend over a larger velocity range, see KI97).
(d) From their velocity dependent morphology, each of the loops shows evidence for shell expansion, but with only half of the shell present. In both cases, the receding side (with respect to galaxy rotation) is open.
(e) Other smaller HI loops and extensions do exist at smaller galactocentric radii.
(f) The parameters of these two HI supershells are as follows: The eastern supershell has a mass, M = 5.9 $\times$ 10^7 M$_\odot$, a radius, R = 3.2 kpc, an expansion velocity, Δv = 51.7 km s^{-1}, a kinematic age, τ = 6.0 $\times$ 10^7 yr, a kinetic energy, E$_{\rm kin}$ = 1.6 $\times$ 10^{54} ergs, and an implied input energy (assuming instantaneous input from supernovae) of E = 2.6 $\times$ 10^{56} ergs. The parameters of the western supershell are: M = 2.3 $\times$ 10^7 M$_\odot$, R = 1.85 kpc, Δv = 41.4 km s^{-1}, τ = 4.4 $\times$ 10^7 yr, E$_{\rm kin}$ = 3.9 $\times$ 10^{53} ergs, and E = 3.4 $\times$ 10^{55} ergs.
(g) The energy needed to create the eastern supershell alone would require a star cluster populated by $> 1.7 \times 10^5$ OB stars, if supernovae and stellar winds are the drivers.
(h) The brighter and more spectacular eastern supershell has associated HI gas which extends as far as 30 kpc beyond the eastern edge of the optical disk and possibly much farther (see Fig. 1a inset). The huge eastern HI extension appears to open up from one side of the eastern shell and extends fairly straight outwards in the radial, rather than the vertical direction as if formed in a short period of time in comparison to galactic rotation.
(i) The galaxy contains a large nonthermal radio halo with a scale height of $\sim$ 5 kpc above the plane (see also de Bruyn & Hummel 1979, Bloemen et al. 1993).
(j) Radio continuum emission appears to be associated with the HI loops, but is not spatially coincident with them. The radio continuum emission extends farther out than the HI supershells, as if "funnelling" along or through the HI features (KI97; Fig. 1b).
(k) NGC 3556 has no obvious interacting companions. The brightest galaxy in the vicinity is the 16th magnitude, MCG+09-19-001, 25$''$ in size, undisturbed in appearance and $\sim$ 12$'$ to the east of NGC 3556. This is most likely a background source.

2.3.2. Other examples

NGC 5775, an interacting galaxy, shows symmetrically placed HI features (Lee et al. 2000) in the sense that HI extensions occur on opposite sides of the major axis in which there appears to be an underlying disturbance; these features occur at similar galactocentric radii, in projection (see also Fig. 3 of Irwin

1994 which shows 3 of the extensions). NGC 2613 (Chaves & Irwin 2000) also shows six HI extensions which occur in pairs symmetrically on either side of the major axis; two of the pairs occur near the ends of the optical disk.

Another potentially very interesting example is M 31. Blitz et al. (1999) show that two massive HI clouds exist symmetrically placed on opposite sides of this galaxy. They bear a remarkable resemblance to extragalactic radio jets. The two clouds are redshifted by $\sim 200\,\mathrm{km\,s^{-1}}$ with respect to the systemic velocity of M 31. Conceivably, this could be explained by ram pressure sweeping as M 31 falls through the IGM towards the Milky Way.

3. A new model for the formation of HI supershells

3.1. Need for a new mechanism

As mentioned above, the galaxy NGC 3556 puts to a severe test both of the standard explanations for the supershell phenomenon, namely: (i) localized starburst (generating intense stellar winds, followed by multiple supernova explosions), and (ii) infall of massive gas clouds on to the galactic disk. The major difficulties faced by these models, as highlighted in KI97, are:

(a) Localized starbursts: The energy needed to create the eastern supershell alone would require a star cluster populated by $> 1.7 \times 10^5$ OB stars. Even for the recently discovered 'super star clusters (SSC)' in some starburst galaxies, not more than 10^4 OB stars are implied (Meurer et al. 1995). There is no indication of an OB association even remotely approaching the level of SSCs at the locations of the supershells in NGC 3556. Since the kinematic ages of the supershells are $\sim 5 \times 10^7$ yr, the starburst would have to have occurred within this time frame. Yet starburst durations and OB association ages are typically also of this order, so some evidence of the starburst might be expected to have survived. No such evidence is presently found, however. NGC 3556 does not show a markedly high supernova rate globally (Irwin et al. 1999) and independent low and high resolution radio continuum observations show no evidence for a source of energy at the bases of the supershells (KI97, Irwin et al. 2000).

(b) Infalling clouds: Several arguments have been advanced against this possibility (KI97). Firstly, this galaxy appears isolated, making the source of the putative clouds puzzlesome. Secondly, to impart sufficient kinetic energy for the creation of the eastern supershell, an infalling cloud of mass $> 10^8\ M_\odot$ would be required. A cloud this massive would easily have been detected on the sensitive HI maps, yet no such cloud or clouds are seen. (An exception would be if the clouds had very narrow line widths, low fractal dimensions and were optically thick, in which case they could have been missed due to low filling factors.) Thirdly, if an encounter with intergalactic clouds has occurred in the past, it would be necessary to postulate that two very massive clouds just happened to fall in parallel to the major axis at opposite ends of the galaxy, roughly at the same time, a scenario which seems implausible. Fourthly, we could instead suggest that a "rain" of HI clouds is infalling (since other high latitude HI structures are also seen in this galaxy), including two which fell in along the major axis at either end. However, in order for the rain to be no longer visible, the infall would have to be completed over a timescale which is less than or equal to the age of the supershells, i.e. a few 10^7 years. This is unlikely since infall timescales are of order a dynamical timescale which is typically a few 10^8 yr.

While these arguments have been applied to NGC 3556 alone, the difficulty with internal energy from starbursting applies to a number of galaxies, as outlined in Sect. 1. Infalling clouds are certainly plausible, but run into difficulties for isolated galaxies such as NGC 3556 and NGC 3044. Barring new information coming to light on these galaxies, we therefore argue that a new model should be considered.

3.2. Outline of the model

As mentioned earlier, the duality of the expanding HI supershells in NGC 3556, together with their locations at the opposite edges of the disk marked by steep density gradients, their Z-symmetric deviations from spherical symmetry, as well as their anomalously large energy requirements (Sect. 2.3.1), together lead us to argue that the origin of these two supershells is linked to the jet phenomenon. In Sect. 2 we have noted several manifestations of jet instabilities giving rise to bubble-shaped features, or shells, in the form of optical nebulosities or non-thermal radio emission in normal spirals and radio galaxies. In the present context of HI supershells, we examine the possibility of the supershell being inflated due to localised instabilities in the radio jets as they plough through the ISM of the disk of NGC 3556. The present discussion should only be viewed as a feasibility check based on energy considerations, and not as a detailed quantitative model for the supershells. Even in the case of NGC 3556, the standard mechanisms for the supershells (Sect. 1) may well have contributed at some level.

According to our proposal, the two radio jets ejected close to the plane of the disk, during the active phase of the nucleus, undergo a rapid *flaring* as they encounter the region of large scale density decline near the outskirts of the galactic disk. Consequently, both synchrotron plasma and the entrained thermal plasma deposited by the jets in these two regions get heated and the resulting high-pressure bubble of hot plasma undergoes a rapid expansion, sweeping the gas-rich ambient medium into the shape of the HI supershells. An idealization to such a situation is the flaring of a jet crossing an ISM/IGM interface, which was first discussed in the context of radio galaxies analytically by Gopal-Krishna & Wiita (1987), followed by two-dimensional (Norman et al. 1988, Wiita et al. 1990, Zhang et al. 1999) and three-dimensional (Loken et al. 1995, Hooda & Wiita 1996, 1998) numerical simulations. The simulations by Loken et al. showed that intermediate power radio jets associated with wide-angle-tail (WAT) sources undergo a rapid flaring upon crossing the ISM/IGM density discontinuity where a moderately supersonic jet becomes subsonic. As shown by the numerical simulations, a density drop of a factor of just a few can cause such a flaring (e.g. Hooda & Wiita 1996). Observational evidence for the jet flaring comes from Wide-Angle-Tail (WAT) radio sources which are associated with the dominant members of rich clusters of galaxies (e.g. O'Donoghue et al. 1993). Further evidence is provided, e.g., by the recent radio/optical/X-ray study of the WAT radio galaxy 3C465 in the Abell cluster A2634 (Sakelliou & Merrifield 1999). Particularly instructive for the present study is the case of the active disk galaxy IRAS 04210+0400; the two ~ 10 kpc long radio jets associated with this disk galaxy are seen to flare up near the opposite optical boundaries of the galaxy (Holloway et al. 1996). It may be noted that during their passage through the inner parts of the galactic disk, the jets are likely to encounter large ISM density fluctuations. However, these are less prone to disrupt the jets because of the higher jet thrust there, combined with the expected small spatial scale of the density fluctuations compared with the jets' cross-section.

Since the postulated radio jets in NGC 3556 are currently too weak for detection, a point which we re-address below, we shall adopt here the jet parameters inferred for another massive disk galaxy, NGC 4258 (Sect. 2.1), and apply them to known conditions in NGC 3556. The jet velocity, as measured from the emission line gas, is *at least* v_j = 2000 km s^{-1} which, together with a density of ρ_j = 0.02 m_p g cm^{-3}, where m_p is the mass of the proton, correspond to a kinetic luminosity of $L_j \sim 10^{42}$ erg s^{-1} (Falcke & Biermann 1999). Assuming that the ram pressure in the jet dominates over the internal thermal pressure, then across the shock front we require $\rho_j \,(v_j - v_s)^2 \;=\; \rho_0 \, v_s^2$, where ρ_0 is the ambient gas density, and v_s is the shock velocity. Taking ρ_0 = 0.26 m_p g cm^{-3} at the positions of the supershells (KI97), we obtain v_s = 435 km s^{-1}. This is slightly higher than the value of $\sim$ 300 km s^{-1} estimated for NGC 4258. The shock velocity puts a minimum timescale on the duration of the jet in this model, since there must be sufficient time for the jet to propagate out to the locations of the supershells at 12 kpc galactocentric radius. Thus, the minimum duration of the jets is 2.7 $\times$ 10^7 yr for the parameters in this illustration.

The mechanical power of the jet would then be L_j = $1/2\, \rho_0 \pi\, R^2\, v_s^3$ = 5 $\times$ 10^{41} erg s^{-1}, where the effective jet radius, R has a typical value of 1 kpc (e.g. Cecil et al. 1995). This is similar to the jet power estimated for the well known spiral galaxy M 51, which is at the low end of the scale of nuclear activity (cf. Ford et al. 1985). In NGC 3556, the integrated mechanical luminosity of the jet over its minimum lifetime is then $\sim$ 4 $\times$ 10^{56} erg. This lower limit is adequate to account for the observed kinetic energy associated with the larger eastern supershell (Sect. 2.3.1). Here we have assumed that the efficiency for converting the input energy into the kinetic energy of the shell is of order 1% as usually taken for the multiple supernova model. For a higher efficiency, the required jet power can be lower.

The expansion of a typical bubble in the ISM should then proceed similarly to previously modelled scenarios, the difference being the source of input energy. Since the input energy is much higher than conventional supernovae, the bubbles are more likely to achieve blowout, providing a natural conduit through which cosmic rays (including those supplied by the jets) can escape into the halo. Thus, the presence of supershells is expected to correlate with the existence of a nonthermal radio halo.

The locations of the anchor points of the two supershells in NGC 3556 suggest that the postulated blasting of each supershell would have occurred at a galactocentric distance which is just past the peak of the HI rotation curve (see Fig. 6 of KI97). The radially outward expansion of each supershell would then expose it to the velocity shear in the medium, exerting a sideways wind pressure counter to the galactic rotation. Due to this, the half of the supershell towards the direction of the galactic rotation would be compressed and hence brightened, whilst the other half would be dragged out due to the velocity shear in the external medium and, consequently, dimmed. Such a deformation of the two supershells from spherical symmetry, in course of their expansion, would give rise to a Z-symmetry, which is consistent with the observations (Sect. 2.3.1; KI97).

The cooling time for the X-ray emitting sheaths around the jets of NGC 4258, assuming unity filling factor, is only 4 $\times$ 10^6 yr (Cecil et al. 1995) and therefore, once the jets have turned off, such a signature of their existence would disappear rapidly. The lifetime of the synchrotron emitting particles in the jets is longer, typically from 10^6 to 10^7 yr. For NGC 4258, it has been estimated to be between 1 to 5 $\times$ 10^7 yr (Martin et al. 1989). However, shorter timescales are possible and will depend on local magnetic field strength and spectral index. For instance, the magnetic field in the north-east radio jet in NGC 1068, which extends to $\sim$ 450 pc from the nucleus, is $\sim 5 \times 10^{-4}$ Gauss and the spectral index is -1 (Wilson & Ulvestad 1987). This gives a synchrotron lifetime of only 1.5 $\times$ 10^5 yr. The particle lifetime is expected to be shorter in shocks where the magnetic field is compressed. Thus, we expect the radio jet in NGC 3556 to fade over a timescale less than the ages of the supershells.

Similar arguments apply to the radio core which is expected to decay faster than the jets, once the nuclear activity has switched off, given the likelihood of a stronger magnetic field and flatter spectral index in the core. Even if some radio emission from a core were to persist after the activity ceases, it may be below the rms noise level of the available maps. Chary & Becklin (1997), for example, estimate the radio luminosity of the core of NGC 4258, which is known to have a supermassive central object of mass 3.6 $\times$ 10^7 $M_\odot$ and a VLBI jet, to be L_{rad} = 100 $L_\odot$. The 2σ noise level of the radio maps of Irwin et al. (2000) corresponds to a radio power of 6.8 $\times$ 10^{17} W Hz^{-1}. Integrating over 10^{11} Hz, this yields a radio luminosity of 180 $L_\odot$. Thus, even if NGC 3556 harbours a radio core of the same luminosity as NGC 4258, it would not have been detected in the observations mentioned above.

4. Summary and possible implications

In this study we have sketched a scenario whereby radio jets ejected during an active nuclear phase in the life of a large spiral galaxy could inflate out of the disk exceptionally large shells, i.e. supershells of neutral hydrogen gas. When applied to the Scd galaxy, NGC 3556, this model can account for each of the several features enumerated in Sect. 2.3.1. In the context of the HI supershells seen in this galaxy, this scheme appears to fare distinctly better than either of the two standard models for supershells which invoke either a starburst induced superwind or an infall of external gas clouds on to the galaxy disk. Thus, the jet-ISM interaction scenario for disk galaxies could effectively supplement the other two mechanisms already proposed for the supershell phenomenon, with a greater relevance whenever the shells are extraordinarily large as well as energetic and occur at large galactocentric distances.

The energy requirement is no longer a major issue in the present model. Even a modest energy input from a 10^7 $M_\odot$ compact object at the galactic nucleus, such as that observed in NGC 4258, is more than adequate to supply the input energy required for the supershells of NGC 3556. This model can therefore account for HI supershells which are difficult to form via conventional processes involving massive star formation, or those occurring in galaxies lacking potentially interacting companions. Larger supershells (or parts thereof, given the probable development of instabilities) may also be predicted, since known central masses and/or accretion rates may well surpass those considered here.

Furthermore, the present model can account for the symmetric HI features in galaxies. For instance, it is more likely that bubbles will be inflated by the propagating jets at galactocentric radii where the ISM density has declined to sufficiently low values for blow-out. At the same time, symmetry is not a generic outcome our model, since local shocks, dictated by the interaction of the jet with local density perturbations, can be important in determining where the bubbles will be inflated. For example, known bubbles in the lobes of radio galaxies (Sect. 2.2) are not always seen to be equidistant on either side of the nucleus.

In our sample illustration (Sect. 3.2), the jets must exist for long enough to reach large galactocentric radii (3×10^7 yr) but need to inject energy over only a fraction of the lifetime of the supershells (2×10^7 yr, or even less, if the efficiency exceeds 1%). The jets presumably switch off thereafter, with the synchrotron emitting particles decaying in 10^6 - 10^7 yr. It is difficult to predict whether jets and HI supershells should co-exist in spirals. Nuclear activity in galaxies is commonly believed to be a transient phenomenon, lasting for $\sim 10^7$–10^8 years (e.g. Eilek 1996, Scheuer 1995; Soltan 1982; Haehnelt & Rees 1993; Ho et al. 1997). If AGN activity occurs on timescales longer than a few $\times 10^7$ yr, this would suggest that there might be disk galaxies in which both phenomena should be observed at the same time. However, such nuclear activity timescales are likely to be more representative of radio galaxies; AGN activity in spirals is probably shorter lived. An important next step is to consider what jet parameters are required to reach large, or at least kpc-scale radii, in traversing the typical ISM of a spiral galaxy.

If jets in spirals both recur and precess, it may be possible to inflate bubbles over a variety of galactocentric radii and azimuthal angles. However, it is unlikely that the "frothy" nature of the HI seen in galaxies such as Holmberg II or the holes in M 31 could be produced by such jets directly without seeing some lingering evidence for the jets as well. Also, the jet phenomenon cannot directly account for features which correlate with the star forming disk, such as some known radio and Hα halos. If there is a connection, it is more likely to be indirect. For example, once the expansion of the postulated jet-blown supershells is halted due to the gravitational pull of the host galaxy, their segments (i.e. HI clumps) would eventually shower back on to the galactic disk, giving rise to secondary shells, bubbles and cavities in the HI component of the disk. The impact could also trigger sporadic bursts of star formation, especially in the outer disk, as seen, e.g., in gas-rich low-surface-brightness galaxies (cf. O'Neil et al. 1997) which are thought to be the present-day remnants of quasars (e.g. Schombert 1998). Thus, much after its cessation, the nuclear activity in gas-rich galaxies may continue to influence the evolution of their disks.

Acknowledgements. It is a pleasure to thank Paul J. Wiita for valuable comments on the manuscript. JI gratefully acknowledges a grant from the Natural Sciences and Engineering Research Council of Canada.

References

Aoki K., Kosugi G., Wilson A.S., Yoshida M., 1999, ApJ 521, 565
Axon D.J., Marconi A., Capetti A., et al., 1998, ApJ 496, 75
Baum S.A., O'Dea C.P., de Koff S., et al., 1996, ApJ 465, L5
Blitz L., Spergel D.N., Teuben P.J., Hartmann D., Burton W.B., 1999, ApJ 514, 818
Bloemen H., Duric N., Irwin J.A., 1993, In: Leahy D.A., Hicks R.B., Venkatesan D. (eds.) 23rd International Cosmic Ray Conference. World Scientific, New Jersey, p. 279
Brinks E., Bajaja E., 1986, A&A 169, 14
Cecil G., Wilson A.S., de Pree C., 1995, ApJ 440, 181
Cecil G., de Pree C.G., Greenhill L.J., Moran J.M., Dopita M.A., 1998, AAS 193.0710
Chary R., Becklin E.E., 1997, ApJ 485, L75
Chaves T., Irwin J.A., 2000, In: Hibbard J.E., Rupen M.P., van Gorkom J.H. (eds.) Gas and Galaxy Evolution. ASP Conf. Ser., in press
Chevalier R.A., 1974, ApJ 188, 501
Cox P., Downes D., 1996, ApJ 473, 219
Dahlem M., Lisenfeld U., Golla G., 1995, ApJ 444, 119
de Bruyn A.G., 1977, A&A 58, 221
de Bruyn A.G., Hummel E., 1979, A&A 73, 196
Dreher J.W., Feigelson E.D., 1984, Nat 308, 43
Efremov Y.N., Elmegreen B.G., Hodge P.W., 1998, ApJ 501, L163
Eilek J.A., 1996, In: Hardee P.E., Bridel A.H., Zensus J.A. (eds.) Energy Transport in Radio Galaxies and Quasars. ASP Conf. Ser. 100, ASP, San Francisco, p. 281
Elmouttie M., Haynes R.F., Jones K.L., Sadler E.M., Ehle M., 1998, MNRAS 297, 1202
Falcke H., Biermann P.L., 1999, A&A 342, 49
Ford H.C., Crane P.C., Jacoby G.H., Lawrie D.G., van der Hulst J M., 1985, ApJ 293, 132
Genzel R., Eckart A., Ott T., Eisenhauer F., 1997, MNRAS 291, 219
Gopal-Krishna, Wiita P.J., 1987, MNRAS 226, 531
Haehnelt M., Rees M., 1993, MNRAS 263, 168
Heiles C., 1979, ApJ 229, 533

Heiles C., 1984, ApJS 55, 585
Herrnstein J.R., Moran J.M., Greenhill L.J., et al.,, 1997, ApJ 475, L17, Erratum: ApJ 482, L113
Ho L.C., Filippenko A.V., Sargent W.L.W., 1997, ApJ 487, 568
Holloway A.J., Steffen W., Pedlar A., et al., 1996, MNRAS 279, 171
Hooda J.S., Wiita P.J., 1996, ApJ 470, 211
Hooda J.S., Wiita P.J., 1998, ApJ 493, 81
Hummel E., van Gorkom J.H., Kotanyi C.G., 1983, ApJ 267, L5
Irwin J.A., 1994, ApJ 429, 618
Irwin J.A., Seaquist E.R., 1990, ApJ 353, 469
Irwin J.A., English J., Sorathia B., 1999, AJ 117, 2102
Irwin J.A., Saikia D.J., English J., 2000, AJ 119, 1592
King D., Irwin J.A., 1997, New Astr. 2, 251 (KI97)
Kinney A.L., 2000, ApJ (July 2000 issue)
Kormendy J., Richstone D., 1995, ARA&A 33, 581
Kukula M.J., Pedlar A., Baum S.A., O'Dea C.P., 1995, MNRAS 276, 1262
Lee S.-W., Irwin J.A., 1997, ApJ 490, 247 (LI97)
Lee S.-W., Irwin J.A., Dettmar R.-J., et al., 2000, in prep.
Lehnert M.D., Heckman T.M., 1996, ApJ 462, 651
Loeb A., Perna R., 1998, ApJ 503, L35
Loken C., Roettiger K., Burns J.O., Norman M., 1995, ApJ 445, 80
Martin P., Roy J.-R., Noreau L., Lo K.Y., 1989, ApJ 345, 707
Meurer G.R., Heckman T.M., Leitherer C., et al., 1995, AJ 110, 2665
Moody J.W., Roming P.W.A., Joner M.D., et al., 1995, AJ 110, 2088
Morrison P., Sadun A., 1996, MNRAS 278, 265
Nagar N.M., Wilson A.S., 1999, ApJ 516, 97
Norman M.L., Burns J.O., Sulkanen M., 1988, Nat 335, 146
Norman C.A., Ikeuchi S., 1989, ApJ 345, 372
O'Donoghue A.A., Eilek J.A., Jones J.M., 1993, ApJ 408, 428
O'Neil K., Bothun G.D., Schombert J., Cornell M.E., Impey C.D., 1997, AJ 114, 2448
Puche D., Westpfahl D., Brinks E., Roy J.-R., 1992, AJ 103, 1841
Rand R.J., 1997, In: van der Hulst J.M. (ed.) The Interstellar Medium in Galaxies. Kluwer, Dordrecht, p. 105
Rand R.J., Stone J.M., 1996, AJ 111,, 190
Rand R.J., van der Hulst J.M., 1993, AJ 105, 2098, Erratum: AJ 107, 392
Rhode K.L., Salzer J.J., Westpfahl D.J., Radice L.A., 1999, AJ 118, 323
Sakelliou I., Merrifield M.R., 1999, MNRAS 305, 417
Scheuer P.A.G., 1995, MNRAS 277, 331
Schombert J., 1998, AJ 116, 1650
Soltan A., 1982, MNRAS 200 115
Tenorio-Tagle G., Bodenheimer P., 1988, ARA&A 26, 145
Ulvestad J.S., Wilson A.S., 1984a, ApJ 278, 544
Ulvestad J.S., Wilson A.S., 1984b, ApJ 285, 439
Ulvestad J.S., Wrobel J.M., Roy A.L., et al., 1999, ApJ 517, L81
van Breugel W., Fomalont E.B., 1984, ApJ 282, L55
van der Marel R.P., 1999, AJ 117, 744
van der Hulst T., Sancisi R., 1988, AJ 95, 1354
Wiita P.J., Rosen A., Norman M.L., 1990, ApJ 350, 545
Wilson A.S., Ulvestad J.S., 1987, ApJ 319, 105
Zhang H.-M., Koide S., Sakai J.-I., 1999, PASJ 51, 449