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SIGNATURES IN A GIANT RADIO GALAXY OF A COSMOLOGICAL SHOCK WAVE AT INTERSECTING FILAMENTS OF GALAXIES

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ABSTRACT

Sensitive images of low-level, Mpc-sized radio cocoons offer new opportunities to probe large scale intergalactic gas flows outside clusters of galaxies. New radio images of high surface brightness sensitivity at strategically chosen wavelengths of the giant radio galaxy NGC 315 (Mack et al. 1997, 1998) reveal significant asymmetries and particularities in the morphology, radio spectrum and polarization of the ejected radio plasma. We argue that the combination of these signatures provides a sensitive probe of an environmental shock wave. Analysis of optical redshifts in NGC 315 vicinity confirms its location to be near, or at a site of large-scale flow collisions in the 100 Mpc sized Pisces-Perseus Supercluster region. NGC 315 resides at the intersection of several galaxy filaments, and its radio plasma serves there as a 'weather station' (Burns 1998) probing the flow of the elusive and previously invisible IGM gas. If our interpretation is correct, this is the first indication for a shock wave in flows caused by the cosmological large scale structure formation, which is located in a filament of galaxies. The possibility that the putative shock wave is a source of gamma-rays and ultra high energy cosmic rays is briefly discussed.

Subject headings: acceleration of particles – shock waves – intergalactic medium – large-scale structure of universe – galaxies: individual (NGC 315) – galaxies: clusters: individual (Pisces-Perseus-Supercluster)

1. INTRODUCTION

Beginning with the first detailed images, it was speculated that the Z-like morphology of the giant, Mpc sized radio galaxy NGC 315 (Fig. 1) is affected by environmental influences (Bridle et al. 1976). New high frequency maps unveil a unusually flat radio spectrum at the end of the Western (W) lobe, indicating that the lobe's CR electrons are freshly re-energized far from AGN or first termination shock. No comparable structure is found in the Eastern (E) lobe. At NGC 315's location several subfilaments of the Pisces-Perseus Supercluster intersect to form the beginning of its main filament (Fig. 2). Gravitationally driven, supersonic flows of intergalactic gas and galaxies onto and along these filaments, and towards the clusters of galaxies will inevitably collide, and form large scale shock waves on the largest conceivable scales (Quilis 1998; Miniati et al. 2000). Therefore NGC 315 resides in an environment where shock waves are indeed expected to be present. In this paper we investigate the hypothesis that such a wave re-energizes the W lobe's electron population.

Large-scale shock waves are the primary heat source in the wider intergalactic medium (IGM), and they also allow measurement of its unknown entropic history (Tozzi et al. 2000). They have been proposed as possible generation sites of intergalactic magnetic fields (Kulsrud et al. 1997; Ryu et al. 1998), of ultra high energy cosmic rays (Norman et al. 1995; Kang et al. 1996, 1997; Siemieniec and Ostrowski 2000), and of the diffuse gamma ray background (Loeb and Waxman 2000; Totani and Kitayama 2000). Prior to this work, merger and accretion shock waves have been detected only inside of galaxy clusters by temperature structures in the X-ray observable cluster gas (Miyaji et al. 1993; Donnelly et al. 1998) or by radio emission from shock accelerated electrons (Enßlin et al. 1998; Roettiger et al. 1999; Enßlin and Gopal-Krishna 2000). Here, the putative shock wave is located in a galaxy filament, on a scale that is 10 - 100 times the dimension of a cluster and with a gas density that is orders of magnitude lower. The new data therefore raises a new possibility of the precise detection and probing of flows in the "filament and bubble" morphology predicted by the theory of cosmological large scale structure formation (Bond et al. 1996, cf.).

2. NGC 315: A COSMIC WEATHER STATION

The giant radio galaxy NGC 315 has two straight, bright radio jets, which form termination shock waves at a distance of 860 kpc (E) and 420 kpc (W) from the galaxy where they are stopped by the intergalactic medium (assuming $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and an EdS cosmology). In the standard model of extended radio sources these shock waves serve as accelerators for the radio emitting relativistic electrons of the jet material. After shock passage the electron energy (E) distribution function is given by a power-law $f(E)\,dE \sim E^{-s}\,dE$ within the radio-observable energy range. This leads to synchrotron emission with a power-law radio frequency (ν) spectrum $F_\nu \sim \nu^{-\alpha}$, with

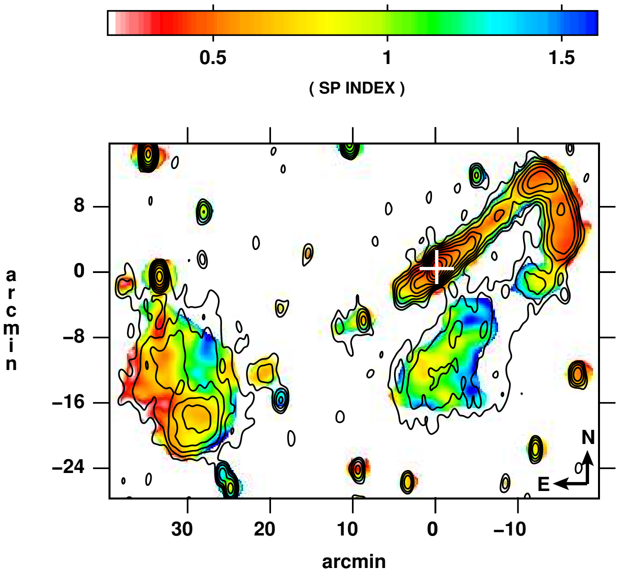

FIG. 1.— 327 MHz radio map of NGC 315 (contours) superimposed on spectral index map between 327 MHz and 600 MHz (Mack et al. 1998). The position of the galaxy is marked. Note that the spectral index in the W tail might be flatter than displayed due to possibly missing 600 MHz flux of extended structures.

$\alpha = (s-1)/2$. In the course of the outflow, subsequent radiative synchrotron and inverse Compton cooling leads to a steepening of the electron spectrum at the highest energies. Together with adiabatic expansion losses this can be expected to produce a progressive fading of the radio plasma beginning at the highest frequencies. When the fading reaches the lowest observable frequencies the radio plasma becomes undetectable and can be called a 'fossil'.

Precession of the jet axis of NGC 315 appears to have produced radio plasma trails of the termination shocks of the jets (Bridle et al. 1976, see our Figs. 1 and 3). The observable part of the E trail is short at higher frequencies; 130 kpc at 1.4 GHz, but 480 kpc at 327 MHz. This conforms to the typical behavior of cooling radio trails. However, an unexpected result was that the W trail could be detected even at the relatively high frequency of 4.8 GHz over a distance of 600 kpc from the termination shock of the W jet, and up to 800 kpc at 327 MHz. The spectral index measured between 327 and 600 MHz is $\alpha_{327}^{600} \approx 0.75...1.25$ – quite flat, as can be seen in Fig. 1. It remains flat even at higher frequencies up to 10.6 MHz (Mack et al. 1998). The morphologies of the two trails are also different, in that the E trail is roughly as one expects for a precessing jet, but the W trail shows a bending 200 kpc away from the hot spot. Finally the W trail has an average radio polarization of 32 ± 9 % at 10.6 MHz.

Three properties of the W trail suggest that an originally symmetrical radio galaxy is "falling", together with its surrounding IGM environment, into an intergalactic shock wave. These are: (i) the unusually flat spectral index up to high radio frequencies at large distances from the point of ejection, (ii) the radio polarization characteristics, and (iii) the bending. The most striking fact (i) is that the electron population is being re-energized in the fossil radio plasma on a large scale. This region is remote from any possible galactic source of fresh electrons. And it is separated from the jet termination point by a

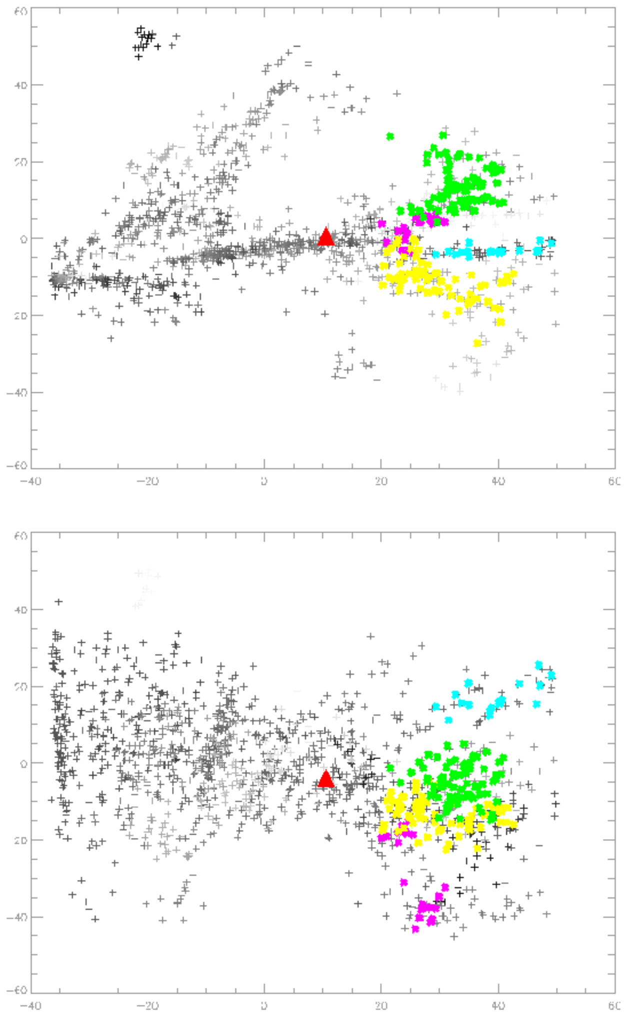

FIG. 2.— Galaxy distribution in the Pisces-Perseus Supercluster sky projection (top) and seen from above in redshift space (bottom). The third dimension is encoded in the grey-scale. Distances are given in Mpc. A density filter was applied to enhance the visual significance of the filamentary structure. The galaxies of the intersecting filaments are colored (blue = II, pink = III, yellow = IV, green = V). The estimated velocity dispersions of the different filaments I-V are $\sigma = 399 \pm 14, 169 \pm 22, 92 \pm 26, 221 \pm 26, 171 \pm 33$km/s. The individual filaments cannot be separated in the intersection region due to their overlap in the redshift space which is caused by their velocity dispersions. Therefore it is not clear which of them hosts NGC 315 (red triangle).

steep spectrum region.

A natural particle acceleration mechanism is compression due to a large scale shock. In the following we pursue this model as the supposed cause of the spectral and polarization properties of the western lobe of NGC315. The consequence is a strong increase of the radio emissivity, which is also expected to be coherently polarized, due to the large scale alignment of the compressed magnetic fields (ii). The degree of polarization depends largely on the angle between the line of sight and the shock normal. The observed polarization suggests this angle to be 5°...20° (Enßlin et al. 1998). However high polarization, also seen in many other extended radio sources, is not a unique test of our putative large sale shock scenario. The shock may well also explain the bending of the W trail (iii) (Fig. 3).

Alternative explanations of the bending are an environmental subsonic wind, or a projection of a special precession history of the jets. However precession should have produced a comparable structure in the eastern lobe and a possible wind cannot explain the spectral flattening at the lobes end.

3. PISCES-PERSEUS SUPERCLUSTER OF GALAXIES

In order to estimate the expected shock strength we analyzed the redshift distribution of galaxies in the Pisces-Perseus Supercluster using the CfA2 redshift catalog (Huchra et al. 1990). Since we are interested in the galaxies' velocity dispersion $\sigma^2 = \langle \vec{v}^2 \rangle$ we had to disentangle the positional information in the redshift by means of statistics. We identified filaments by eye and estimated their orientations in redshift space using the main axis of the inertia tensor of the galaxy distribution within the chosen sub-volumes (Fig. 2). These will approximately be identical to the real-space axes if we can assume that the (statistical) distribution of galaxies in a filament has a cylindrical symmetry with respect to the filament axis, and that the velocity dispersion of galaxies is isotropic. These assumptions allow us further to subtract the angular diameter (defined as the angular dispersion times the distance) of the filament from the redshift dispersion, yielding a rough estimate of the required velocity dispersion.

The main filament (I) has $\sigma_{\rm I} = 400 \pm 15\,{\rm km/s}$ whereas the smaller filaments (II...V) have $\sigma_{\rm II...V}$ between $90...220\,{\rm km/s}$, a substantial difference. Since the velocity dispersion of the galaxies and the IGM-gas of the filaments should be comparable, this translates into temperatures of $kT_{\rm I} = 280\,{\rm eV}$ and $kT_{\rm II...V} = 15...85\,{\rm eV}$. The gas in one of the smaller filaments might get heated by a shock wave when it flows into the deeper gravitational potential of the main filament. Such a shock wave is expected to have a temperature jump $kT_2/kT_1 = kT_{\rm I}/kT_{\rm II...IV} = 3.3...20$, a compression ratio $R_{\rm gas} = 2.9...3.8$, a pressure jump $P_2/P_1 = 9.6...75$, and a shock velocity of $v_{\rm shock} = 460...520\,{\rm km/s}$ (Landau and Lifschitz 1966). The subscript 1 (2) refers to the upstream (downstream) region of the shock wave. In all following estimates, the indicated parameter ranges result from the above shock strength ranges.

4. PARTICLE ACCELERATION

Quantities such as the shock wave orientation, projection geometry, speed of the jet precession, and galaxy motion cannot be completely constrained by the available data. We restrict ourselves only to the assumption that the W trail became compressed several 10 Myr after deposition of the radio plasma in a shock caused by one of the merging galaxy filaments. A shock wave is only able to penetrate into the radio plasma if the (unknown) internal sound velocity is smaller than the shock speed. If it is, diffusive shock acceleration of the existing relativistic electron population at the shock would explain the re-population of the higher electron energies. If not, the alternative possibility is that the radio plasma gets adiabatically compressed by the shock. This also leads to an energy gain of the relativistic electron population. We demonstrate below that either scenario is able to explain the unusual W trail of NGC 315.

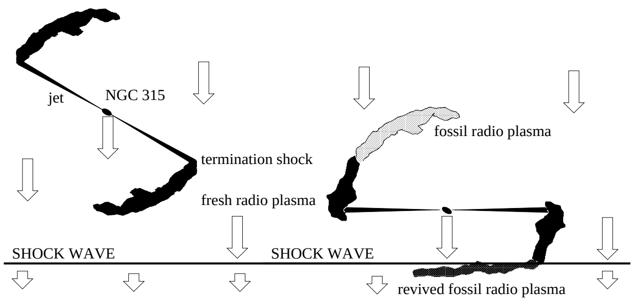

FIG. 3.— Sketch of the discussed scenario for NGC 315 and its environment. Left: the undisturbed radio galaxy approaching a shock wave of the embedding gas flow. Right: the observed present stage, where the preceding radio plasma gets revived in the shock wave.

4.1. *Shock Acceleration*

Shock acceleration produces a power law electron energy distribution with a spectral index $s = (R+2)/(R-1)$ (Drury 1983), where R is the compression ratio of the accelerating shock wave inside the radio plasma. Since the radio plasma can have a relativistic equation of state, R can in principle be bigger than $R_{\rm gas}$. But using $R = R_{\rm gas}$ for illustration gives $s = 2.1...2.6$, which leads to a radio spectral index of $\alpha = 0.53...0.79$. Superposition of re-accelerated electrons with different ages produces a steepening of α by 0.5 above some break frequency. Cooling after the re-acceleration successively removes the highest frequency emission. The observed spectral indices (Fig. 1) are consistent with the expectations in the shock acceleration scenario. A key physical test is whether the shock has enough power to generate re-accelerated electrons in a sufficient number. The rate of kinetic energy dissipation by the shock wave in the surface $A = 200 \times 600\,{\rm kpc}^2$ of the 'revived' W trail is $Q = \frac{1}{2}\,\varrho\, v_{\rm shock}^3\, A\,(1 - 1/R_{\rm gas}^2) = 2.5...3.8 \cdot 10^{42}\,{\rm erg/s}$. Here ϱ is the upstream mass density which we assume to be $\varrho = 5 \cdot 10^{-29}\,{\rm g\,cm^{-3}}$, following the estimate in Mack et al. (1998) of a few times $1.7 \cdot 10^{-29}\,{\rm g\,cm^{-3}}$. The radio luminosity of the revived W trail is only $3.7 \cdot 10^{40}\,{\rm erg/s}$ (Mack et al. 1998), $\leq 1\%$ of the dissipated kinetic energy Q. This indicates that the radio electron population can be explained with a reasonable shock efficiency.

4.2. *Adiabatic Acceleration*

Adiabatic compression increases the energy density of the relativistic electrons and magnetic fields by $R^{4/3}$. Here, R is the compression of the radio plasma in the shock, given for a fully relativistic equation of state by $R = (P_2/P_1)^{3/4} = 5.4...26$. The synchrotron luminosity for an electron population with spectral index s increases by $R^{2\,s/3}$. The surface brightness increases probably less drastically, due to the more extended morphology of the radio plasma after compression. An observable brightening is only possible if the upper electron energy cutoff $E_{\rm max}$ is high enough to allow synchrotron radiation at the observed frequencies. Synchrotron and inverse Compton aging of the fossil electron population should have produced a cutoff at $E_{\rm max} = 310\,{\rm GeV}\,(t/{\rm Myr})^{-1}\,((u_B + u_{\rm cmb})/({\rm eV\,cm^{-3}}))^{-1}$ (Enßlin and Gopal-Krishna 2000), where t is the age of the fossil radio plasma (after passage of the termination shock), u_B the magnetic and $u_{\rm cmb} = 0.28\,{\rm eV\,cm^{-3}}$ the cosmic microwave background energy density. $E_{\rm max}$ corresponds to a cutoff in the synchrotron spectrum at $\nu_{\max} = 16\,\mathrm{MHz}\,(E_{\max}/\mathrm{GeV})^2\,(B/\mu\mathrm{G})$. The compression increases $E_{\max}$ by $R^{1/3}$, the magnetic field strength B by $R^{2/3}$, and thus the upper frequency cutoff by $R^{4/3}$. This can be used to infer a maximum age the fossil radio plasma can have, for the compression wave to revive the emission at frequency ν, which is

$$t_{\max} = \frac{39\,\mathrm{Myr}\,R^{2/3}}{(u_B + u_{\mathrm{cmb}})/(\mathrm{eV\,cm^{-3}})}\sqrt{\frac{B/\mu\mathrm{G}}{\nu/\mathrm{GHz}}}\,.$$

Given that detection was made at a frequency as high as $\nu = 10.6$ GHz, and the assumption of an initial magnetic field strength of $B = 0.5\,\mu$G (Mack et al. 1998) in the trail we obtain $t_{\max} = 93...260$ Myr. More detailed calculations, following the formalism described in Enßlin and Gopal-Krishna (2000), show that an age of < 100 Myr is more realistic when we allow for the enhanced cooling during the process of compression.

5. GAMMA RAYS

It has been proposed that shocks of the large scale structure formation accelerate electrons up to energies at which they can scatter the cosmic microwave background into the gamma-ray regime (Loeb and Waxman 2000; Totani and Kitayama 2000). If these electrons receive 5 % of the dissipated energy and have a flat spectral index of $s = 2$ they could explain the observed diffuse gamma ray background. The putative shock wave indicated by NGC 315 would imply that we have an ideal testbed for this hypothesis. We assume the same efficiency, but allow for the steeper spectral index due to non-maximal compression ($R_{\mathrm{gas}} = 2.9...3.8 < 4 \rightarrow s = 2.1...2.6 > 2$). This gives an expected gamma ray luminosity of $F_\gamma(> E_\gamma) = 3\cdot\ 10^{-9}\,(E_\gamma/100\,\mathrm{MeV})^{-1.03}\,\mathrm{photon\ cm^{-2}\,s^{-1}}$ for $s = 2.1$ and $F_\gamma(> E_\gamma) = 10^{-11}\,(E_\gamma/100\,\mathrm{MeV})^{-1.29}\,\mathrm{photon\ cm^{-2}\,s^{-1}}$ for $s = 2.6$, where the shock surface was assumed to be 10 Mpc^2. This is consistent with upper limits from the EGRET satellite, but it could be detectable by the future GLAST experiment.

6. CONCLUSION

We have shown that the properties of the ejected radio plasma from the giant radio galaxy NGC 315 can be naturally explained by a transit through a powerful shock wave. Such a shock wave should result from collisions of cosmological flows along the intersecting galaxy filaments in the Pisces-Perseus Supercluster. This kind of observation provides a new method of exploring the tenuous baryonic matter between galaxies (Enßlin et al. 1998; Mack et al. 1998; Wellman et al. 1997). The proposed scenario for NGC 315 suggests that the IGM already becomes shocked outside of clusters (Tozzi et al. 2000), and that the proposed large-scale structure shock wave origin of the gamma ray background should be testable (Loeb and Waxman 2000; Totani and Kitayama 2000). Of course an independent confirmation of the shock is still necessary. Possible strategies are very deep X-ray observations and the search for low frequency, diffuse radio sources associated with the shock – similar to the cluster radio relic sources found at cluster merger shock waves. The ability of radio galaxies to trace environmental shock waves would be further supported if other examples of interaction of radio sources with shock wave could be identified. Also, reactions of the interstellar medium of galaxies which are passing through a shock wave – as in Abell 1367 (Gavazzi et al. 1995; Enßlin et al. 1998; Donnelly et al. 1998) – might be used to reveal shock waves outside clusters of galaxies.

Finally we note that one of the three doublets of ultra-high energy cosmic ray particle arrivals reported by the AGASA experiment (Hayashida et al. 1996) lies in the direction of the Pisces-Perseus Supercluster. This may be an indication of a connection between large-scale intergalactic shocks and the acceleration of cosmic rays (Norman et al. 1995; Kang et al. 1996, 1997; Siemieniec and Ostrowski 2000).

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