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# Dark Spots, Bubbles, and Shells in the Lobes of Extragalactic Radio Sources

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**Abstract.** Based on maps of the extragalactic radio sources Cyg A, Her A, Cen A, 3C 277.3 and others, arguments are given that the twin-jets from the respective active galactic nucleus ram their channels repeatedly through thin, massive shells. The jets are thereby temporarily choked and blow radio bubbles. Warm shell matter in the cocoon shows up radio-dark through electron-scattering.

*Key words*: jets—lobes—shells around galaxies—Cyg A—Her A—radio bubbles

## 1. Introduction

Maps of extragalactic radio sources with high dynamic range and radio-optical overlay maps have shown considerable fine structure of the lobes (radio, Cyg A: Perley, Dreher & Cowan 1984; Dreher *et al.* 1984; Her A: Dreher & Feigelson 1984; 3C 310: van Breugel & Fomalont 1984; 3C 382: Strom, Willis & Wilson 1978; 3C 219: Perley *et al* 1980; 3C 433: van Breugel *et al.* 1983; optical, 3C 277.3: van Breugel *et al.* 1985b; NGC 541: van Breugel *et al.* 1985a; NGC 7385: Simkin, Bicknell & Bosma 1984; Fornax A: Schweizer 1980, Ekers *et al.* 1983; 3C 293: van Breugel *et al.* 1984). There are clear to likely indications that the radio hotspots are associated with optical continuum radiation (Cyg A: Kronberg, van den Bergh & Button 1977; 3C 33 S: Rudnick *et al.* 1981; Meisenheimer & Röser 1986; 3C 273: Röser & Meisenheimer 1986; further: Crane, Tyson & Saslaw 1983).

The radio fine structure of Cyg A shows two (narrow) jets in emission, cylindrical and loop-like emission 'filaments', and two hotspots in each lobe (*cf.* Figs 1a, b). It also shows 'dark spots' associated with the hotspots, and perhaps dark lanes at right angles to the jets (Fig. 1c). We shall interpret these radio-dark features as due to electron-scattering by filamentary matter whose mass amounts to at least $10^{10}\ M_{\odot}$. The filamentary matter is thought to traverse the halo in the form of thin, heavy partial shells, as evidenced by the mentioned radio-dark lanes in the case of Cyg A, by optical emission in the case of Cen A (Malin, Quinn & Graham 1983) and by radio depolarization in the case of 3C 277.3 (van Breugel *et al.* 1985b). These partial shells appear to be rather common (Malin & Carter 1983; Quinn 1984; Schweizer 1986). In the case of Cen A, Gopal-Krishna & Saripalli (1984) have presented overlay evidence that the shells interact with the jets. Kundt & Krause (1985) have argued that the shells consist of filamentary matter ejected supersonically by the galactic nucleus during active epochs—which matter is continually reionised by ram-pressure heating and/or background UV.

These thin, massive partial shells in the haloes of galaxies can make their appearance directly, as quasi-circular radio or optical lanes. Indirectly they are indicated by the large mass needed to give rise to the radio-dark spots of Cyg A, and also by the radio 'bubbles' seen in Her A, 3C 310, 3C 277.3, 3C 219 and others. Such bubbles are thought to be the results of 'jet-choking' (van Breugel & Fomalont 1984): A thin layer of heavy material temporarily reduces the advance speed of the beam's head considerably, in proportion to $\rho^{-1/2}$. As a result of such temporary choking, or stalling, the beam head does not advance at a constant speed but rather at two very different speeds, like a drill eating its way through a sandwich door (at constant thrust). During shell crossing, a huge amount of beam plasma is dumped in a short beam segment. Its explosive expansion sweeps thermal plasma and magnetic fields out in the shape of a strongly magnetised quasi-spherical layer: a radio bubble. These bubbles are reminiscent of a glass-blower's craft. They are observed to have circumferential magnetic fields, in accordance with the suggested explanation (*e.g.* Dreher & Feigelson 1984; van Breugel & Fomalont 1984). We believe that many observed lobe morphologies can be understood as the result of a steady beam ramming its channel through a strongly inhomogeneous environment.

Another environmental effect, not elaborated in this communication, is channel destruction by shear motion of the IGM, in particular at the edge of a galactic halo.

## 2. The radio-dark spots of Cyg A

In Fig. 1c we have drawn what we consider dark spots, and dark lanes, in the lobes of Cyg A. Most remarkable is the dark spot in front of radio hotspot B, in the north-preceding component (*cf.* Alexander, Brown & Scott 1984). It has less than 10 per cent of the peak brightness of the adjacent hotspot B, most clearly obtained from an intensity cut (personal communication by John Dreher; see also Fig. 2 of Hargrave & Ryle 1976). It is hugging hotspot B. It may or may not coincide with an optical source of $J$-magnitude 22 (Kronberg, van den Bergh & Button 1977, in particular the erratum; also $R$ band CCD image of P. Hiltner 1986, personal communication).

It is highly unlikely that the synchrotron-emitting lobes have cylindrical holes aligned with the line-of-sight and correlated with the hotspots. We interpret the radio-dark spots as (front-side) pockets, or cushions, of warm matter scattering the radio photons out of the line-of-sight. As we shall see, the alternative possibility of free-free absorption would imply intolerably high optical emission.

A scattering screen of optical depth $\tau$ reduces the intensity by the factor $e^{-\tau}$. For the dark spot hugging B we need $\tau \gtrsim 1$, hence

$$1 \lesssim \tau_{\text{sc}} = \sigma_{\text{T}} \int n_{\text{e}} \mathrm{d}s = \left(\int n_{\text{e}} \mathrm{d}s\right)_{24.2} \tag{1}$$

where $\sigma_{\text{T}}$ = Thomson cross-section and $n_{\text{e}}$ = electron number density. This estimate envisages the dark spot as a combined effect of scattering plus absence of emission, *i.e.*,

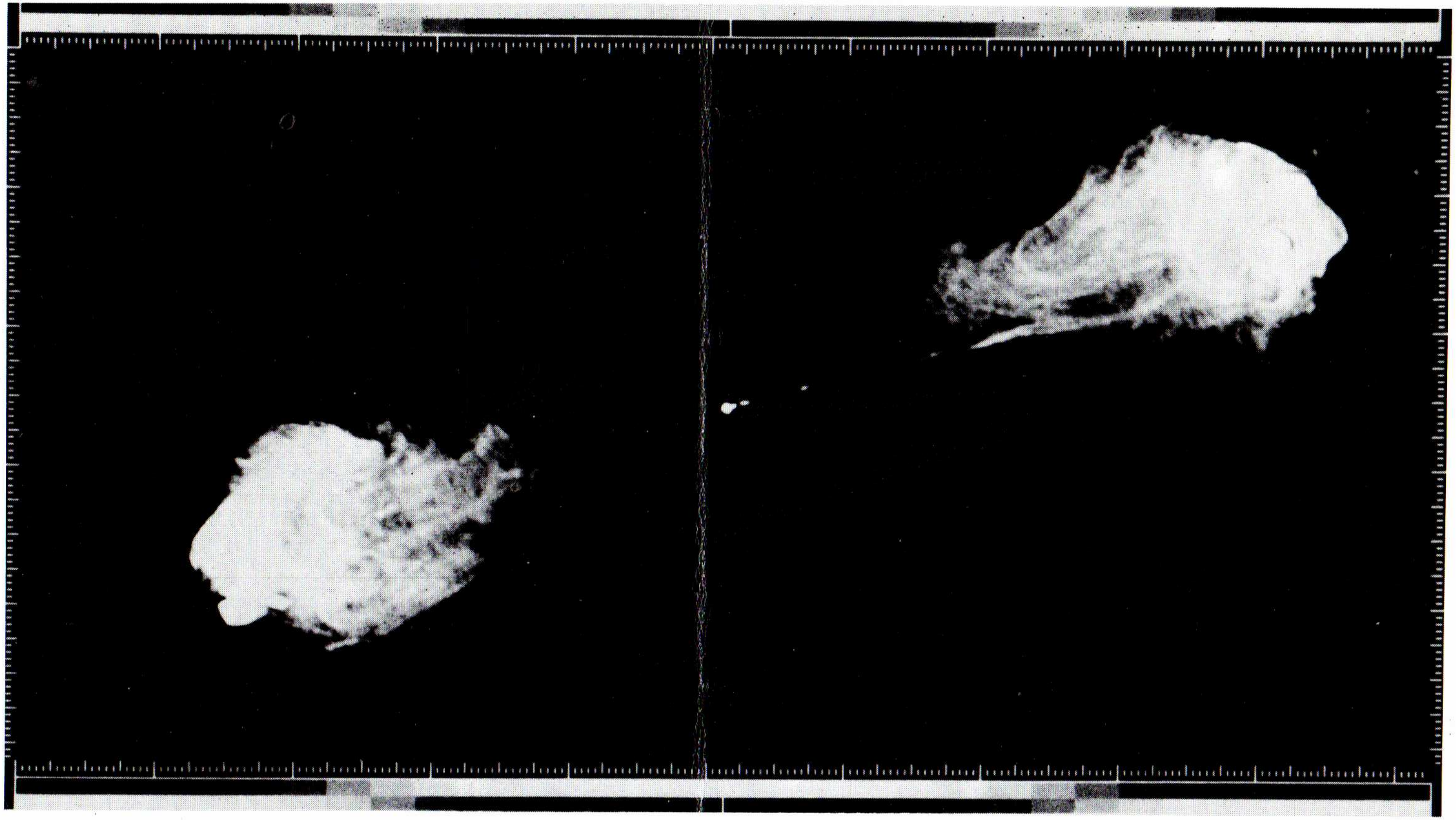

**Figure 1a.** Radio photograph of Cyg A at 5 GHz, courtesy of John Dreher.

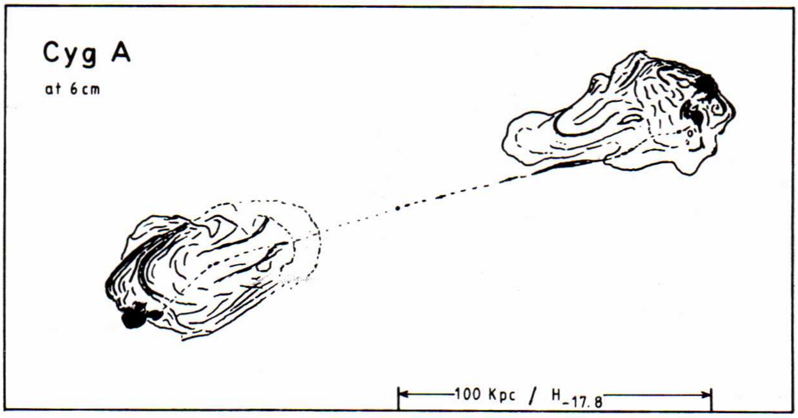

**Figure 1b.** Our interpretation of the bright emission features in Fig. 1a (as a negative).

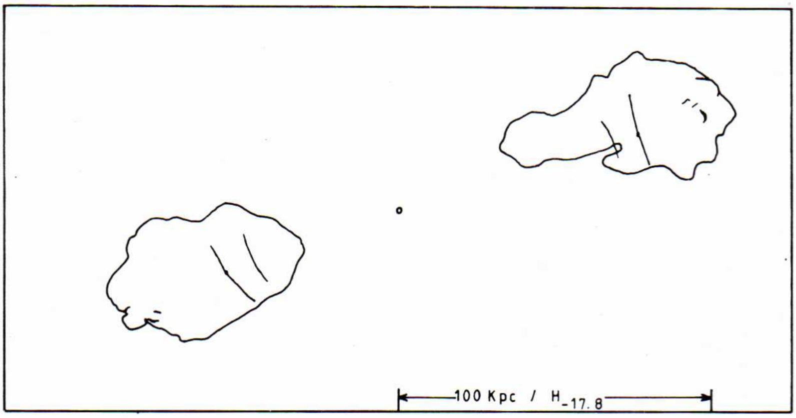

**Figure 1c.** Our interpretation of the (dark) scattering features in Fig. 1a (as a positive). It is not clear whether or not we have overinterpreted the maps in places, but the features show up at different frequencies evaluated both with CLEAN and with maximum entropy algorithm.

absence of relativistic electrons. We approximate the scattering pocket by a cylindrical segment transverse to the beam, of area $A \simeq (3\,\mathrm{kpc}/H_{-17.8})^2$, thickness $d \simeq \sqrt{A}/5$, whence $\int \mathrm{d}s \simeq \sqrt{A}$; ($H$ = Hubble constant, $H_{-17.8} := H/50\,\mathrm{km\,s^{-1}}$ $\mathrm{Mpc}^{-1}$; $z(\mathrm{Cyg\ A}) = 0.056$). This yields for the average electron density throughout the pocket:

$$\langle n_\mathrm{e} \rangle \simeq 10^{2.2}\,\mathrm{cm}^{-3} H_{-17.8}. \tag{2}$$

Here the equality sign need not be trusted: If the pocket is part of an extended shell transverse to the beam, the effective scattering column length $\int \mathrm{d}s$ may be $> \sqrt{A}$, and $\langle n_\mathrm{e} \rangle < 10^{2.2}\,\mathrm{cm}^{-3}$ may hold for this longer column. We shall find much lower estimates for $\langle n_\mathrm{e} \rangle$ in the next section.

An independent estimate of $n_\mathrm{e}$ near hotspot B results from pressure balance with the nonthermal source. From $B^2/8\pi = 2n_\mathrm{e}kT$ and $B_\mathrm{eq} = 2.2 \times 10^{-4}$ G (Alexander, Brown & Scott 1984) we get

$$n_\mathrm{e} \simeq B^2/16\pi kT \lesssim 10^3\,\mathrm{cm}^{-3}/T_4 \tag{3}$$

so that an electron density of $n_\mathrm{e} = 10^{2.5}\,\mathrm{cm}^{-3}$ would imply a temperature $T \lesssim 3 \times 10^4$ K of the scattering medium.

An uncertainty in this latter estimate comes from the fact that we do not know the volume filling factor $f$ of the scattering 'pocket'. But the total mass $\Delta M$ of the scattering region is determined by the dispersion measure $\int n_\mathrm{e}\,\mathrm{d}s$ (*cf.* Equation 1):

$$\Delta M = f m_\mathrm{p} n_\mathrm{e} A d = m_\mathrm{p} \int n_\mathrm{e} \mathrm{d}s \sqrt{A} \mathrm{d} \simeq 10^{43.7}\,\mathrm{g} \lesssim 10^{10} M_\odot, \tag{4}$$

a mass which is much larger than naively expected near the hotspot. The true thickness $d$ of the layer with $n_\mathrm{e} \simeq 10^{2.5}\,\mathrm{cm}^{-3}$ is probably $\ll \sqrt{A}$. Emission shells around isolated elliptical galaxies have estimated column densities of order $N_\mathrm{e} \lesssim 10^{21}\,\mathrm{cm}^{-2}$, corresponding to $d \lesssim$ pc (instead of $\sqrt{A}/5 = 0.6$ kpc) (based on QSO absorption lines, and on HI emission and absorption haloes: Kundt & Krause 1985).

We are thus forced to assume that the dark spot has a larger extent than mapped and a correspondingly smaller (average) electron density. Note that

$$n_\mathrm{e} = \rho_\mathrm{amb} v^2/2kT \simeq 10\,\mathrm{cm}^{-3} (n_\mathrm{amb})_{-3}/T_4 \tag{5}$$

follows for ram pressure balance of a filamentary shell moving transsonically through a hot medium of (hydrogen) number density $n_\mathrm{amb} = 10^{-3}\,\mathrm{cm}^{-3}$. This number is probably a better estimate than Equation 2.

What average mass density $\rho$ do we expect in the distant halo of Cyg A? X-ray observations of poor galaxy clusters suggest asymptotic intergalactic medium (IGM) densities $n_\mathrm{IGM}$ of order $10^{-5}\,\mathrm{cm}^{-3}$ whereas at the centre of a cluster the density can reach $10^{-2}\,\mathrm{cm}^{-3}$ (Canizares *et al.* 1983). Guilbert & Fabian (1986) even suggest IGM densities $\lesssim 10^{-6}\,\mathrm{cm}^{-3}$, based on the assumption of local temperature equilibrium between electrons and protons. For gravitational heating, one would expect comparable velocities of protons and electrons and thus arrive at somewhat higher estimates of the IGM density (Kundt & Krause 1985). But Cyg A lies in a dense environment whose average electron number density at $r \simeq 10^2$ kpc has been determined from X-ray maps as $n_\mathrm{e} = 10^{-2.2}\,\mathrm{cm}^{-3}$ (Arnaud *et al.* 1984). This value is likely an overestimate because it ignores clumping, because it would yield too small an advance velocity of the hotspots (heads) and because Faraday depolarization is low (Hargrave & Ryle 1974). We prefer $n_\mathrm{e} \lesssim 10^{-3}\,\mathrm{cm}^{-3}$.

A lower estimate of the mass $\Delta M$ in the pocket in front of hotspot B can be obtained from the assumption that the beam head has swept clean (and condensed) a cylindrical volume comparable in length $l$ to its last straight segment:

$$\Delta M \gtrsim \rho_{\rm amb} A l \simeq 10^{39.5}\,{\rm g}(n_{\rm amb})_{-3} \simeq 10^{6}\,M_{\odot}. \tag{6}$$

This estimate falls short of the one in Equation (4) needed to get appreciable scattering; we are forced to postulate the presence of much higher mass densities in the distant halo of Cyg A. We could of course invoke a chance encounter of the beam with some (satellite) dwarf galaxy, but the morphology of the south-following head is very similar, and so is the morphology of 3C 219 (Perley *et al.* 1980) and others. The presence of a thin, massive shell is much more plausible, particularly in view of the dark lanes probably observed nearer to the central galaxy (Fig. 1c). The dark lanes are also indicated as linear depolarization features in Fig. 8 of Hargrave & Ryle (1974).

Yet another interpretation of the large mass needed would be to invoke substantial mass entrainment by the jets. De Young (1986) estimates that up to $10^{9}\,M_{\odot}$ can be entrained by a strong jet. This estimate is, however, based on a heavier jet material than relativistic pair plasma (Kundt & Gopal-Krishna 1981) and appears implausible in view of the very small observed velocities of the channel walls, of order 300 km s$^{-1}$, and of the metal-poorness of the material emitting near the radio hotspots (*e.g.* van Breugel *et al.* 1985b).

## 3. Optical constraints on the radio-dark spots of Cyg A

So far we have interpreted the radio-dark features in Cyg A as due to electron scattering and have estimated the required masses to be larger than $10^{10}\,M_{\odot}$. An alternative interpretation could invoke free-free (ff) absorption (at frequencies reaching up to $\nu = 10^{10}$ Hz: *cf.* Lang 1978):

$$\tau_{\rm ff} = \left(\int n_{\rm e}^{2}\,{\rm d}s\right)_{26.8} / T_{4}^{3/2} \nu_{10}^{2}. \tag{7}$$

A required $\tau_{\rm ff} \gtrsim 1$ at $1 \lesssim T_4 \lesssim 3$ would therefore ask for an emission measure $\int n_{\rm e}^{2}\,{\rm d}s = 10^{27.2\pm0.5}\,{\rm cm}^{-5}$, or $\langle n_{\rm e}^{2}\rangle \gtrsim 10^{5.2}\,{\rm cm}^{-6}$ which, at first sight, looks consistent with our estimates in Equations (2, 3) (for unit filling factor $f$).

But an emission measure of order $10^{27.2}\,{\rm cm}^{-5}$ would give rise to thermal free-free radiation of power (*cf.* Lang 1978):

$$L_{\rm ff} = 10^{-25} \int n_{\rm e}^{2}\,{\rm d}s\, T_{4}^{1/2} (A/5)\,{\rm erg\,cm^{3}\,s^{-1}} \simeq 10^{45.5\pm0.5}\,{\rm erg\,s^{-1}} \tag{8}$$

at temperature $T \gtrsim 10^{4}$ K, and to free-bound (fb) radiation (in particular Lyman and Balmer jump; *cf.* Lang 1978):

$$L_{\rm fb} \gtrsim 10^{2} L_{\rm ff}/T_{4} \simeq 10^{47.2\pm0.5}\,{\rm erg\,s^{-1}} \tag{9}$$

which are much higher than observed, and much higher than available via the beam. Note that a temperature $T$ largely in excess of $10^{4}$ K would imply an intolerably high emission measure through Equation (7), and would at the same time be unexpected because of the shape of the cooling curve which predicts runaway instability above $10^{5}$ K (Gaetz & Salpeter 1983).

Observationally, Kronberg, van den Bergh & Button (1977) put an upper bound of $J \geqslant 22$ mag on the optical power of the dark spot, corresponding to $M_J \geqslant -13.2$

$+5 \log H_{-17.8}$ for an estimated (galactic) $A_v = 1.2$ mag, or $L_J \leqslant 10^{42.5}$ erg s$^{-1}$. In the case of no identification, this estimate would drop by at least two magnitudes, *i.e.*, below $10^{42}$ erg s$^{-1}$ in the $J$-band. These upper bounds conflict with our estimate (9) by a factor $\gtrsim 10^3$ whereby allowance has been made for a (high) temperature near $3 \times 10^4$ K for which most of the ff- (and fb)-radiation would be emitted at higher than $J$-band frequencies. We conclude that $\langle n_e^2 \rangle \lesssim 10^{2.2}$ cm$^{-6}$ must hold, as in Equation (5) above, *i.e.* that ff-absorption of radio power by the warm cushion near hotspot B is insignificant.

Independently of Kronberg *et al.*'s optical constraint, there is the total-available-power constraint: Ram-pressure forcing of the ambient medium by the advancing beam head liberates a maximal power (*cf.* Hobbs *et al.* 1978):

$$L_{\text{ram}} = \rho_{\text{amb}} v_{\text{head}}^3 A \simeq L_{\text{jet}} \beta_{\text{head}} \lesssim 10^{44}\,\text{erg s}^{-1} (n_{\text{amb}})_{-3}^{-1/2} \tag{10}$$

(the latter because of $\rho_{\text{amb}} v_{\text{head}}^2 = \text{constant}$) which must be reduced to $\lesssim 10^{42}$ erg s$^{-1}$ for an encounter with a massive shell, of $n_{\text{amb}} \simeq 10$ cm$^{-3}$. This estimate agrees with the one by Kronberg *et al.*

In our interpretation, the jet advances at an irregular speed, of over $v_{\text{head}} \simeq 0.1c$ when traversing the average halo medium and some $10^2$ times slower when piercing a dense shell. Its average advance speed is therefore given by $0.1c$ multiplied by the fraction of the time during which it is not choked. This fraction may be of order 0.5, in accord with the fact that very bright hotspots are common but not necessarily present in young sources. This estimate is also consistent with the ones by Winter *et al.* (1980) and Alexander, Brown & Scott (1984) which yield $\beta_h = 0.05\, H_{-17.8}$ for suitable interpretation.

## 4. Conclusions

Our interpretation of the dark features and bright features in the lobes of the extragalactic radio sources is based on the assumption that relativistic plasma rams a narrow channel (jet) through the ambient medium (Kundt & Gopal-Krishna 1981; Kundt 1987). At the end of a jet, ram pressure is converted into static pressure across a terminal shock, and subsonic expansion follows supersonic supply. This scenario shares certain features with a glass-blower's art, or with the (imaginary) inflating of a rubber balloon through a straw whose far end is kept near the far end of the balloon. In the case of an extragalactic radio source, the balloon is realized by the cocoon—filled with shocked beam plasma—and observed as the lobe.

In this picture, part of the ambient medium stays near the jet, in the form of a (porous) channel wall, due to Rayleigh-Taylor instabilities during ramming, whereas a large fraction of the ambient medium is swept to the outer edge of the cocoon during the (Rayleigh-Taylor-stable) relaxation phase (of decreasing pressure). The swept-up ambient medium is expected to form cylindrical shells around the jet. Such radio-bright cylindrical shells are indeed indicated in Cyg A, yet offset from the present jets (Fig. 1b). This offset may be a consequence of the swinging of the beam into a new direction, as discussed at length by Kundt & Gopal-Krishna (1986). In the case of Cyg A, both jets have swung south.

The new element introduced in the present paper are the multiple, quasi-spherical partial shells, consisting of ram-pressure confined filaments of mass density

$\rho \simeq 10^{-23}\,\mathrm{g\,cm^{-3}}$, which repeatedly choke the ramming beams, give rise to radio bubbles and can make their appearance directly as radio-dark lanes, depolarized lanes, or faint optical emission shells.

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This work has been launched by a long conversation with John Dreher during which he stressed the possible significance of the radio-dark spots in Cyg A, and presented us the original radio-photograph reproduced in Fig. 1a. Discussions with Robert Laing and Peter Scheuer are likewise acknowledged. One of us (L.S.) gratefully acknowledges the support and hospitality of the Institut für Astrophysik at which this work has been done. Both of us thank Mr. Hutschenreiter for the reproduction of Fig. 1a.

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Dear Alan, 13 Jan. 1990

have you had a chance of looking at Eric Lerner's forcefree filaments? He wants them to emit the CBR, but they radiate below 1 MHz; am I mistaken?

I enjoyed talking to you during the poster session.

Best wishes from

Wolfgang Kundt.