A SUGGESTED CLASSIFICATION AND EXPLANATION FOR HOTSPOTS IN SOME POWERFUL RADIO SOURCES

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1. A CLASSIFICATION SCHEME FOR HOTSPOT COMPLEXES IN POWERFUL DOUBLE RADIO SOURCES

High resolution (1"→0".1) maps of the outer complexes of some "well formed" powerful radio sources suggest that we can now distinguish two physically distinct types of outer hotspots. We denote them as type "A" and "B" and describe them as follows: Type A hotspots, illustrated in Figure 1, occur at the outer leading edge, and have a cusp-like, or otherwise elongated shape. This strongly suggests that their shape and energy density are determined by the ram-pressure interaction between the end of a beam or momentum flux "pipeline", and the ambient i.g.m. Magnetic fields appear well-ordered along the cusp (Laing, 1981). The surface brightness of well-resolved Type A hotspots leads to a velocity of advance (V_a) which is typically $10^3 \rightarrow 10^4 (\rho^{-1}_{ig_{-27}})$km/s (ignoring the ion energy).

As the schematic illustration in Fig. 1 shows, Type B hotspots generally lie off the A hotspot-galaxy/QSO axis, and are also behind the Type A hotspots. In at least some cases, such as illustrated in Fig. 1, they are more compact and have a higher minimum energy density than the outer, Type A hotspots. Synchrotron lifetimes in the B hotspot of 3C351N are $\lesssim 10^4$ yrs, which is less than the light travel time from A- to the B-hotspot. The B-hotspots in 3C351N and CygAW appear to

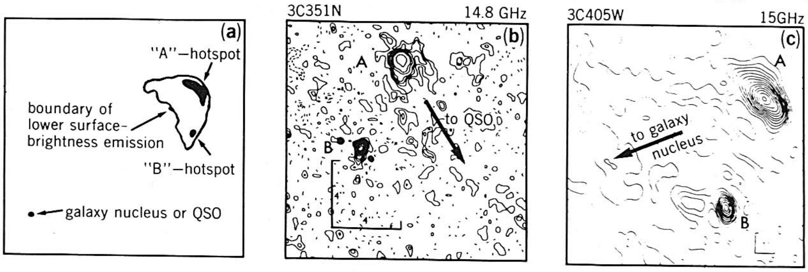

Fig. 1. "A" and "B" hotspots illustrated schematically (a), and in λ2cm maps of 3C351N (Kronberg et al. 1980) and CygAW (Hargrave & Ryle 1976) (b and c).

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occur near the lobe-i.g.m. interface. In both of these cases the resolution is not yet sufficient to define their morphology or magnetic field structure in detail. Higher resolution ($\lesssim$0.1 arcsec) observations will be useful in further elucidating the structure of B-hotspots, in particular the question as to how they are confined.

While a number of strong extragalactic source lobes exhibit the A- and B-hotspot characteristics just described, we must emphasize that many others do not. Examples of the latter are sources having structure like 3C31 and 3C449, head-tail sources, and sources having complex or z-shaped structure. In other cases, eg. 3C9 at 1" resolution, one lobe appears to have at least a cusp-shaped A-hotspot, whereas the opposite radio lobe has an entirely different structure.

The nature of the B-hotspots is intriguing. The short radiative lifetimes of their constituent electrons imply that particle acceleration *is occuring in the B hotspots.* Prima facie ram pressure arguments suggest that, if the B-hotspots are at the end of the beam, they ought to have advanced fastest, hence furthest from the galaxy/QSO - which is contrary to observation in the examples we have cited. In the following section we propose an explanation for the A-B hotspot phenomenon.

2. A SUGGESTED MODEL FOR A AND B HOTSPOTS

We begin with the assumption that the A hotspots occur at the end of the beam which deposits the energy from the galaxy/QSO. The B hotspots arise from instabilities which form along or near the lobe-i.g.m. interface as the A hotspot advances into the ambient medium. The observed circumferential geometry of magnetic field lines in A hotspots provides a natural channel for rapid transport, backwards and off axis, of relativistic electrons from the A hotspot. These are then trapped and accelerated in instabilities at the lobe-i.g.m. interface, and in this way form B hotspots. The relatively infrequent appearance of strong B hotspots within a given radio lobe can be explained if they form and dissipate on timescales short compared with the dynamic lifetime of the radio lobe. Their relative proximity to the A hotspots ($\lesssim$20% of A-to-QSO) suggests that they are causally connected to the A hotspot phenomenon, and further that conditions for B hotspot formation are favourable off-axis and not too far from the leading edge of the outer lobe.

Since we can now resolve A hotspots and, hence estimate the minimum internal energy density (ε) of the relativistic gas, pressure balance with the i.g.m. of density ρ gives an estimate of the velocity of advance, $V_a \simeq 5770\ (\varepsilon_{-9}/\rho_{-27})^{1/2}$ km/s. For typical sources this is comparable to the Alfvén speed, derived from the assumption of equipartition, at the ejecta-i.g.m. interface ($V_A = 8920\ B_{-4}(\rho_{-27})^{-1/2}$ km/s), and the ion sound speed, $V_s \simeq 1200\ T_8^{1/2}$ km/s. It is also not much greater than typical i.g.m. orbital or turbulent velocities $100 \lesssim V_t \lesssim 1000$ km/s (ε,ρ,B, and T in c.g.s.). The similarity of all these numbers (which we expect a priori if the Mach number of the beam flow is not very large) suggests that the shear velocities near the interface behind the A hotspot are of the requisite magnitude to stimulate the growth of the Kelvin-Helmholtz type instabilities. In their classical form these will propagate with wave number $k_z(=2\frac{\pi}{\lambda}\cos\theta)$ and amplitude a, and will grow to a limit given by $ka\sim1$ (Gerwin 1968). The characteristic growth time is $\sim(\lambda/\Delta V)\sqrt{\rho_{ig}/\rho_{lobe}}$, where ΔV is the velocity differential which will stimulate suitable wave growth. As the field is amplified due to being "stretched" (the surface area of the interface is increased by the instability), electrons will gain energy by betatron acceleration on approximately the same timescale, and thus produce a B-hotspot. Taking $\Delta V<0.1c$, $\lambda<500$ pc we find that the kinetic energy available $(\rho_{ig}(\Delta V)^3\lambda^2)$ is comparable to the inferred particle energy in the B-hotspot. Once formed, however, the B hotspots are probably short-lived. Since instability growth slows as $a\sim\lambda$, acceleration of electrons should become less efficient (eventually due primarily to stochastic processes). Then short radiative lifetimes will cause the spot to fade. We might therefore expect to see the faded, fainter, remains of B hotspots at lower surface brightness levels more commonly than the "hot" B hotspots in Fig. 1. At the University of Minnesota this work was supported by NSF grant AST79-00304, and at the University of Toronto by NSERC grant No. A5713.

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DISCUSSION

LAING: I have observed several examples of hot-spots (e.g., in 3C 20, 133, 196) whose morphologies are inconsistent with the predictions of your model. The main problem is that the limb-brightened cusp in the diffuse subcomponent always points away from the compact subcomponent, whereas in your model one would expect it to point away from the associated galaxy or quasar. In addition, in 3C 20 and 3C 196, the compact subcomponents are on the source axis. (R. A. Laing, this volume.)

KRONBERG: We agree that 3C 196 (like Hydra A and other probably similar sources) do not appear to have our canonical form of A-hotspot, and are presumably subject to a somewhat different set of physical conditions. In our suggested model, however, the A-cusp axis could deviate from the axis to the QSO (as is apparent in Cyg AW) due to the effect of local i.g.m. velocities at the outer lobes (V_t) which are non-negligible relative to V_a.

DE YOUNG: I have difficulty seeing how the nonlinear Kelvin-Helmholtz instability will always produce just one compression region which gives the enhanced synchrotron emission.

JONES: First, we would like to emphasize that, in our suggested model, approximately one young B hotspot is seen at a given time; over a larger sample, we don't expect always to see exactly one B hotspot. Since synchrotron emissivity is such a strong function of the field amplification ($\varepsilon \sim B^{7/2}$ in the simplest case) the enhanced spot should be strongly concentrated in a region (our B hotspot) where the largest instabilities go non-linear ($a \sim \lambda \sim r$). Larry Smarr's numerical calculations, shown at this meeting, support the idea that this region is fairly clearly defined.