CENTRAL RADIO SOURCES

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We make to ourselves pictures of facts.
Ludwig Wittgenstein, Tractatus Logico-philosophicus

ABSTRACT

The compact radio sources in the nuclei of most active galaxies lie closer to their centers of activity than any other region accessible to observation, excepting only the broad emission line region. They provide uniquely strong evidence for bulk motion of matter at relativistic velocities, encouraging the belief that the activity originates in a gravitational potential well whose escape velocity is of order the speed of light. We review the observational facts and several theoretical pictures of them. We do not repeat the excellent reviews of the early observations (Kellerman and Pauliny-Toth 1981) or the basic physics of compact radio sources (Begelman, Blandford, and Rees 1984), nor do we show VLBI maps (which the reader may enjoy in the proceedings of IAU Symposium 110, 1984). Instead, we have tried to emphasize those places where systematic observations could help to distinguish the true theoretical picture from the many competing forgeries.

I. INTRODUCTION

Compact radio source; central radio source; flat-spectrum radio source; nuclear radio source. These terms have become practically synonymous as observations have revealed that extragalactic radio sources with a flat spectrum ($S_\nu \propto \nu^{-\alpha}$, $\alpha \lesssim 0.4$ at frequencies 100 MHz$\lesssim \nu \lesssim$ 10 GHz) nearly always have a linear size <1 kpc and coincide in position with the nucleus of an active galaxy. Conversely, sufficiently sensitive observations of an active galaxy discovered by some other technique generally reveal a small flat-spectrum radio source in the nucleus.

The optical continuum luminosity of active galactic nuclei (AGNs) ranges over some seven orders of magnitude. Optical astronomers have subdivided this range into two-order of magnitude pieces named 'Quasar', 'Seyfert', and 'LINER'. By contrast, the single name 'compact radio source' embraces objects differing in radio luminosity by twelve orders of magnitude —from the 10^{34} erg s^{-1} of our Galactic center to the 10^{46} erg s^{-1} of 2134+004. This range of luminosity is even greater than that spanned by the objects we call stars (the luminosity of an O-type supergiant being some 10^{10} times that of a brown dwarf at the edge of the hydrogen-burning main sequence). Unfortunately the additional orders of magnitude have not produced a corresponding increase in the depth of our understanding; it would be charitable to describe the theory of compact radio sources as 'less developed' than the theory of stellar structure.

This underdevelopment is due in large measure to the fact that the objects in question are in neither hydrostatic nor local thermodynamic equilibrium. Non-equilibrium physics is poorly understood; such scratches as have been made on its surface reveal a bewildering richness of phenomena, phenomena which tend to be ill-conditioned, in the sense that infinitesimal changes in the boundary conditions lead to large changes in the results. The perennially unsolved problems in the theory of stellar structure are largely those associated with departures from equilibrium (convection, rotation-induced circulation, coronal heating, stellar winds, non-LTE effects). Yet even to lowest order, compact radio sources are far from equilibrium.

Despite these depressing prospects, one may find some comfort in the fact that the most interesting phenomena in another famous non-equilibrium system—the earth's atmosphere—can be understood on the basis of dimensional analysis alone. So, while awaiting the coming of self-contained and predictive theories of magnetohydrodynamic turbulence, non-linear saturation of plasma instabilities, and relativistic particle acceleration, it seems worthwhile to examine the phenomenology and the energetics, and try what we can learn from simple physics and dimensional analysis.

II. INTENSITIES AND SPECTRA

a) Emission Mechanisms

The most striking feature of the radio sources in the inner tens of parsecs of active galactic nuclei is the flatness of their spectra ($S_\nu \sim \nu^\alpha$, $-0.3 \lesssim \alpha \lesssim 0.3$) and their variability on timescales $t_{\rm var}$ ranging from months to tens of years. Estimates of the angular size of the emitting region as $\theta \lesssim ct_{\rm var}/D$ (where D is the angular-diameter distance to the source) first showed that the brightness temperature of these compact sources generally lay in the range 10^{10} K $\lesssim T_b \lesssim 10^{14}$ K, clearly demonstrating that the radiation was nonthermal. Two possibilities suggested themselves for the radiation mechanism: coherent processes (due to stimulated emission, as in masers, or due to particle bunching, as in pulsars) and incoherent sychrotron radiation. There is no natural reason why coherent processes should lead to brightness temperatures near 10^{12} K (though with some ingenuity, a saturation mechanism could probably be concocted for contrived models). There *is*, however, an obvious reason why incoherent synchrotron radiation should limit itself to brightness temperatures near 10^{12} K, and it is for this reason that it is now generally believed to be the relevant radiation mechanism. Relativistic electrons of Lorentz factor γ in a magnetic field of B Gauss self-absorb their own radiation of characteristic frequency

$$\nu \simeq 0.3\gamma^2 \left(\frac{eB}{2\pi m_e c}\right) \simeq \gamma^2 B \text{ MHz} \tag{1}$$

when the brightness temperature reaches

$$T_{sa} \simeq \gamma m_e c^2/k \simeq 6 \times 10^9 \gamma \, \mathrm{K}. \tag{2}$$

Synchrotron radiation may be thought of as inverse-Compton scattering of the virtual photons of a magnetic field. Hence the average rate of energy loss per particle by an isotropic distribution of particles with velocity βc is $\dot{E} = -(4/3)\sigma_T c \gamma^2 \beta^2 U_{\mathrm{TOT}}$, where $U_{\mathrm{TOT}} = U_{mag} + U_{phot}$. Here $U_{mag} = B^2/8\pi$, which contributes to synchrotron radiation, and $U_{phot} = 4\pi J/c$ is the total energy density in radiation, which contributes to inverse Compton scattering. When the energy density in the synchrotron spectrum radiated by the particles exceeds the magnetic energy density, the particlez0cegin to inverse Compton scatter their own radiation (the so-called synchrotron self-Compton, or SSC process), leading to a rate of energy loss $\propto \gamma^4 U_{mag}$. A slight further increase in the brightness temperature will cause the energy density in this scattered radiation to exceed that in synchrotron radiation, leading to energy loss $\propto \gamma^6 U_{mag}$, and the process quickly runs away — until the last-scattered photons have energies $> \gamma^{-1} m_e c^2$, at which point energy conservation and the Klein-Nishina cross-section prohibit further up-scattering. Since the hard gamma-ray background flux does not allow the gamma-ray luminosity of each compact radio source to be much greater than its radio luminosity, it is clear that this runaway has not occurred. Thus we deduce that if the radiation from compact radio sources is incoherent synchrotron radiation, the brightness temperature (measured in a Lorentz frame in which the radiation electrons have an isotropic distribution — i.e. in their fluid rest-frame) cannot much exceed the one which causes the runaway to begin: $kT_b \nu_s^3/c^3 < B^2/8\pi$. Relating γ and T_b by equation (2), and using the expression equation (1) for ν_s, one finds that for a self-absorbed source, $\gamma < 400 \ \mathrm{B}^{-1/7}$, corresponding to $T_b < 2 \times 10^{12} B^{-1/7} \mathrm{K}$ (more sophisticated calculations which allow for a distribution of electron energies may be found in Jones, O'Dell, and Stein 1974; the existence of this limit was first pointed out by Hoyle, Burbidge and Sargent in 1966). Some powerful and rapidly variable sources have brightness temperatures exceeding this limit by two or three orders of magnitude. These sources are generally BL Lac objects and optically violently variable quasars, but at least one powerful broad-emission-line radio galaxy (3C111) exceeds the limit (but by a smaller factor; Hine and Scheuer 1980). The probable reasons for this are discussed below in the subsections on low- and high-frequency variability.

b) Source Structure

The astrophysical signatures of synchrotron radiation are high ($\gtrsim 30\%$) linear polarization and a characteristic $S_\nu \propto \nu^{-0.7}$ spectrum. The first is inherent in the emission mechanism when the magnetic field is anisotropic (but not necessarily *ordered* — Laing 1980); the second signature is probably due to a universal mechanism of accelerating electrons to relativistic energies (by scattering them back and forth in the converging flow maintained by a shock front —*cf.* Bell 1978; for a recent review, see Drury 1983). The radiation from compact radio sources has neither of these characteristic signatures: it has low ($\sim 3\%$) polarization and a flat $S_\nu \propto \nu^{-\alpha}$, $-0.3 \lesssim \alpha \lesssim 0.3$) spectrum. The fact that the brightness temperatures cluster about the Compton limit (§II.*a*) encourages the belief that the emission is nevertheless synchrotron. It therefore behooves us to inquire into the reasons for its disguise.

The synchrotron radiation from a homogeneous box containing magnetic field and relativistic electrons with a suitably truncated powerlaw distribution of Lorentz factors $N(\gamma)d\gamma \propto \gamma^{-p}d\gamma$ (Fermi acceleration in non-relativistic shocks gives $p \gtrsim 2$) has flux density $S_\nu \propto \nu^2\gamma \propto \nu^{5/2}$ [using eq. (1)] for $\nu < \nu_*$, and $S_\nu \propto \nu^{-(p-1)/2}$ for $\nu > \nu_*$, where ν_* is the frequency at which the box becomes optically thick to synchrotron self-absorption. To order of magnitude, ν_* is just the frequency at which S_ν — calculated on the assumption that the source is optically thin— becomes equal to the source function $S_\nu \simeq \gamma m_e c^2(\nu^2/c^2)$ [where γ is to be related to ν by (II.1)].

Since no compact radio source exhibits the characteristic $\nu^{5/2}$ spectrum, the nuclear sources are evidently *not* homogeneous. The characteristic flat spectrum must therefore result from a superposition of many homogeneous boxes whose luminosities and self-absorption frequencies are carefully adjusted so that the sum has a flat spectrum. That this should be universally so seems quite remarkable, and has become known as the "Cosmic conspiracy." Multifrequency VLBI observations strongly suggest that this is nevertheless the correct explanation. They show that the sources are typically resolved into several blobs of emission, all but one of which have at high frequencies the steep spectra characteristic of synchrotron radiation elsewhere in the universe. Summing the spectra from the observed blobs magically reproduces the flat spectrum of the unresolved source (Cotton *et al.* 1980; Wittels *et al.* 1982; Unwin *et al.* 1983; Bartel *et al.* 1984a; see also the cleverly made spectral index maps of a close pair of quasars in Marcaide and Shapiro 1984). This universal conspiracy is a clue to the structure of the source.

Consider a free jet or a spherical wind. In the absence of shear or dynamo action, the magnetic field $B \propto r^{-1}$. At a given frequency, the flux from the source will come mainly from the synchrotron photosphere (radius $r_*(\nu)$) whose source function $S_\nu \propto \gamma\nu^2$. Thus $F_\nu^{TOT} \propto S_\nu(r_*)r_*^2 \propto \gamma^5 B^2(r_*)r_*^2$. In a source with a flat spectrum and $B \propto r^{-1}$, at every frequency the observer is looking at electrons of the same Lorentz factor (a few hundred for typical parameters), and the source size (photospheric radius) $r_* \propto \nu^{-1}$. There is therefore a well-defined *radius–frequency relation.* Flux at higher frequencies comes from deeper in the source.

The simple model considered above predicts that the source size would be proportional to the observing wavelength, and therefore that VLBI observations with a fixed baseline should show the same fractional resolution of the source at all wavelengths. More complicated models (Reynolds and McKee 1980; Marscher 1980; Königl 1981) make different predictions, and may thus be testable. If the magnetic field falls more steeply than r^{-1}, then $r_* \propto \lambda^\beta$, $\beta < 1$, and the source will be more resolved at high frequency. If the jet is collimating rather than conical, $r_* \propto \lambda^\beta$, $\beta > 1$, and the source will be more completely resolved at low frequency than at high.

The spectra of active galactic nuclei invariably steepen above 10^{13} Hz. The radius-frequency mapping tells us that this implies the existence of some characteristic *inner* radius in the source. Scaling from $r_* \sim$ 10pc at 1 GHz according to the simple $r_* \propto \nu^{-1}$ relation, we infer that the inner edge is at a radius of order $10^{15.5}$cm, which is not inconsistent with the expectations of black hole models.

A 'humped' spectrum (deficient at low frequencies) would, in this simple picture, imply the existence of a characteristic *outer* radius. In fact sources with this type of spectrum are identified with "compact doubles" (Phillips and Mutel 1982; Pearson *et al.* 1984). These appear to be more distant animals of the species whose nearby representatives are classified as stifled jets (van Breugel 1984; van Breugel *et al.* 1984 and references therein; Wilson and Ulvestad 1983 and references therein). Wright (1983) has made the interesting observation that QSR's of very high redshift are much more likely to exhibit this type of spectrum than low redshift QSRs (cf. also Menon 1983). This is consistent with one's natural prejudice that galaxies at high redshifts should have more gas at higher pressure and thus be more apt to stifle their jets. VLBI mapping of high-redshift quasars (combined with long-slit spectroscopy at Space Telescope resolution) has much to teach us about the evolution of the interstellar medium in galaxies.

III. LOW FREQUENCY VARIABLES — A RED HERRING?

The reality of low frequency variability of compact extragalactic radio sources is now well established (cf. papers in Cotton and Spangler 1982). Since for a given flux density S_ν, the brightness temperature T_b inferred for a source variable on timescale

t_{var} varies as $T_b \propto S_\nu \nu^{-2} t_{var}^{-1}$, rapid variability at low frequencies causes the greatest embarassment to the 'Compton limit'. Low frequency variability is seen exclusively in flat-spectrum compact sources, which often (but certainly not always) exhibit high frequency variability as well. It might appear that there was thus a watertight case for an intrinsic origin. Suspicions were, however, aroused by the fact that there was no apparent correlation between source variability at frequencies above 1 GHz and that below 1 GHz (Fanti *et al.* 1982).

Following the elegant demonstration by Sieber (1982) that the timescale for low-frequency variability of *pulsars* was strongly correlated with their dispersion measure, there has been a flurry of theoretical activity examining light propagation through large-scale density fluctuations in the interstellar medium (Rickett, Coles and Bourgois 1984; Coles and Felice 1984; Blandford and Narayan 1985; Goodman and Narayan 1985). As a result, it now seems likely that refractive effects in the interstellar medium of our own galaxy are the cause of most low-frequency variability. The small–amplitude (~ 2%) flickering on timescales of a week seen at intermediate frequencies (Heeschen 1984) is probably of the same origin.

Seen through an inhomogeneous medium (bad window glass or the local interstellar medium) a point source will appear both blurred and displaced. The blurring is caused by *diffraction* by irregularities with a scale smaller than the Fresnel radius $R_F \simeq \sqrt{\lambda D} = 10^{11.7} \lambda_m^{1/2} D_{kpc}^{1/2}$cm ($\lambda_m$ is the wavelength measured in meters; D_{kpc} is the distance D from the observer to the middle of the scattering medium, measured in kpc). The displacement is caused by *refraction* by irregularities with a scale larger than R_F.

It is conventional to assume that the fluctuations of electron density in the interstellar medium have a three-dimensional power spectrum $\Phi(k) \propto k^{-\beta}$, where k is the wave-number of the fluctuation (which here has characteristic scale $a \sim 2\pi/k$). Unconvincing physical arguments and consistency with data on pulsar scintillation suggest that $3 \lesssim \beta \lesssim 5$. If the interstellar medium were homogeneous, unmagnetized, and everywhere subsonic, one might expect turbulence with a Kolmogorov spectrum, giving $\beta = 11/3$. For the given scale-free power-spectrum, the electron density fluctuations near wavenumber k have amplitude given by $\langle \delta n_e^2 \rangle \propto k^3 \Phi(k) \propto k^{3-\beta}$. Hence on a scale a, $\delta n_e \propto a^{\frac{\beta-3}{2}}$.

The index of refraction n for an electromagnetic wave of wavelength λ propagating through a sea of free electrons (density n_e) is

$$n = 1 - \frac{n_e r_o \lambda^2}{2\pi} , \tag{3}$$

where $r_o = e^2/m_e c^2$ is the classical radius of the electron. Snell's law shows that in passing through a blob of size a whose index of refraction differs from that of the surroundings by an amount δn, a light ray will be deflected by an angle

$$\delta\theta \sim \delta n \sim \delta n_e \frac{r_o \lambda^2}{2\pi} . \tag{4}$$

In propagating through a distance D, the ray will encounter $\sim D/a$ blobs of size a. Their density fluctuations have random sign and a characteristic magnitude given by the power spectrum. The ray's random walk leads to an rms scattering angle caused by fluctuations of scale a

$$\theta_{rms}(a) \sim \left(\frac{D}{a}\right)^{1/2} \delta\theta \propto a^{\frac{\beta-4}{2}} D^{1/2} \lambda^2 . \tag{5}$$

If $\beta < 4$, the smallest scales dominate the scattering; if $\beta > 4$, the largest scales dominate. Observations of pulsars indicate that the integral effect of diffractive scattering by irregularities with scales $a < R_F$ is to smear the image to an angular size

$$\theta_d \sim \lambda_m^2 D_{kpc}^{1/2} \text{mas} . \tag{6}$$

The rays contributing to this image had a maximum separation $\theta_d D \sim 10^{13}\lambda_m^2 D_{kpc}^{3/2}$cm. For $D \sim 1$ kpc and $\lambda > 10$ cm, $\theta_d D$ exceeds R_F, so the scintillation will be strong. The diffraction pattern at the earth has a spatial scale $\sim \lambda/\theta_d$; when observed through a sufficiently narrow bandpass (typically ~ 0.2 MHz for $\lambda \sim 1$ m), the earth's motion relative to the scattering interstellar medium (at velocity $v \sim 100$ km s^{-1}) will cause the flux to vary (scintillate) on a timescale $\sim \lambda/v\theta_d \sim 10^3$s. This scintillation will be observed only if the true angular size of the source is sufficiently small: less than θ_F^2/θ_d, where $\theta_F = R_F/D$.

Refraction of the image by irregularities of scale $\sim \theta D$ will alternately focus and defocus it, causing the *broadband* flux to vary by a fractional amount

$$\frac{\delta I}{I} \sim \frac{\theta_{rms}(a = \theta D)}{\theta} . \tag{7}$$

Here θ is the apparent angular size of the source, which is the larger of its true angular size and the angular size θ_d [cf. eq. (6)] of the blurred spot created by diffractive scattering. As the earth moves through the refraction pattern, the source will vary on a timescale $\sim \theta D/v \sim 10^6 \theta_{mas} D_{kpc}$s. From equations (5) and (7) we see that $\delta I/I \propto \theta^{\frac{\beta-6}{2}}$, so that larger sources will show smaller intensity variations. This plausibly explains the correlation that only flat-spectrum sources exhibit low-frequency variablity: only they are small enough to be significantly focussed by the weak "lenses" in the interstellar medium. The predicted timescales and amplitudes of variation agree with those seen in low frequency variables and Heeschen's (1982) intermediate frequency flickering (Rickett *et al.* 1984). Goodman and Narayan (1985) have explicitly demonstrated that in the strong-scintillation limit the properties of diffractive *scintillation* depend only upon $|\beta - 4|$, but that for $\beta > 4$ a source of angular size $\theta < \theta_d$ will have a fractal structure (rather than the smooth gaussian profile produced if $\beta < 4$) and will vary by $\delta I/I \sim 1$, independent of wavelength. Observations at low frequency of pulsars and compact extragalactic radio sources may tell us more about the structure of turbulence in the local interstellar medium than they tell us about the sources themselves.

IV. MAPPING AND VLBI

By a happy accident, the lifetime of an astronomer, measured in units of the Hubble time, is slightly greater than the reciprocal of the radius of the earth, measured in centimeters. This means that Very Long Baseline Interferometry (VLBI) at centimeter wavelengths* can resolve at cosmic distances objects known to be variable on their light-crossing times. These measurements have confirmed the angular sizes and brightness temperatures deduced from (high-frequency) variability arguments. Most spectacular, however, has been the observation that several of the objects whose brightness temperature exceeds the Compton limit of 10^{12} K exhibit superluminal motion. This confirmed the prediction (Rees 1967) that the high brightness temperature was due to bulk motion of the emitting regions at relativistic velocities. For reviews of the observations, the reader may consult Kellerman and Pauliny-Toth (1981) and the proceedings of IAU Symposium No. 110, *VLBI and Compact Radio Sources.*

The observations there described have taught us that on the 1–100 pc scales probed by VLBI,

- the radio sources are one-sided in their emission (to jet/counterjet brightness ratios exceeding 50 to 1 —cf. D.L. Jones *et al.* 1985).

- the radio emission is asymmetrical in the same sense as the large-scale structure is asymmetrical, in each of a dozen well-studied cases. This strongly suggests that the asymmetry

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* Short enough to be unaffected by refraction in the interstellar medium!

is not due to asymmetries in the jets' environment, since the interstellar medium deep in the nucleus of the galaxy would be unlikely to know of or share any asymmetry in the extragalactic medium. Either the jet is truly created one-sided (at least in its emission properties), or the asymmetry is only apparent, an effect of relativistic beaming.

- the jets are knotty and curved, not smooth and straight.

- the flat spectra are the result of adding the fluxes from a compact core with a rising spectrum and an extended 'jet' or 'blob' with a descending spectrum (cf. §II).

- except in isolated unconfirmed cases, superluminal motion is always an expansion, the extended blob moving away from the stationary core (cf. §VIII.c).

- besides the core-dominated flat-spectrum radio sources and the large-scale ($\gtrsim$ 50 kpc) steep-spectrum radio sources with weak flat-spectrum cores, there is a large population of steep-spectrum compact sources, most of whose flux comes from a region of complex morphology and a scale of a few kiloparsecs (Peacock and Wall 1982; Simon 1983; Pearson *et al.* 1984). They are very similar to the radio sources seen in nearby Seyferts and interacting gas-rich radio galaxies (van Breugel 1984).

The next three sections discuss fluid phenomena involving relativistic bulk motion. These appear to provide the most promising explanation of the observations.

V. DRY WATER JETS

Due to aberration, time compression and Doppler shifts, emitting regions moving at relativistic velocity in directions close to the line of sight tend to be over-represented in our observations. To illustrate the consequent selection effects we consider in turn:

a) Standard Candles at Random Angles to the Line of Sight

In a steady flow, emitting material moving with velocity $\vec{\beta}c$ at an angle θ to the direction of the line of sight $\vec{n}$ will have an apparent brightness $A(\theta) = (1 - \vec{\beta} \cdot \vec{n})^{-(2+\alpha)}$ times greater than it would if seen face-on ($\theta = \pi/2$). This is strictly valid only if the source is optically thin, with spectral index α, but it is approximately correct for a self-absorbed source in a scale-free atmosphere, provided one uses the *observed* integrated spectral index ($\simeq 0$ for compact radio sources) rather than the spectral index of local emission ($\simeq 0.7$).

On the authority of Ryle and Longair (1967), many authors persist in using an exponent of $(3 + \alpha)$ instead of $(2 + \alpha)$. This is *never* correct in a steady flow (e.g. a smooth jet), which necessarily occupies a well-defined volume in the observer's frame. It is appropriate *only* if all the emission comes from a moving (and hence non-steady) *spherical* blob —as might be the case for a short time after an outburst near the photosphere of an optically thick source. If the emitting blob is non-spherical, different lines of sight will have different (aberrated) path-lengths through the blob and the exponent $(3 + \alpha)$ will no longer be appropriate.* If the blob is very optically thick, the flux depends on the projected surface area. If the non-spherical blob is only marginally optically thick (as seems likely: the knots seen with VLBI become visible as they move out of the optically thick core), the angular dependence of

* In fact, if the blob is highly elongated in the direction of its motion, the angle-dependent path-length causes the exponent to become $(2 + \alpha)$ again!

the flux can be very complicated, since some lines of sight will be optically thin, and others optically thick (*cf.* Lind and Blandford 1985).

Consider an ensemble of smooth, bipolar flat-spectrum jets, identical in every way except for the orientation of their axes with respect to the line of sight. The flux $S(\theta)$ from a jet at angle θ is $S(\theta) = S_\perp \frac{1}{2}[(1-\beta\cos\theta)^{-(2+\alpha)} + (1+\beta\cos\theta)^{-(2+\alpha)}]$, where $S_\perp = S(\pi/2)$. This being a monotonic function of θ, the fraction of sources $\mathcal{P}(> S)$ with flux greater than some value $S(\theta)$ is just the probability that a source's axis lies within θ of the line of sight: $(1-\cos\theta)$. For $\gamma = (1-\beta^2)^{-1/2} \gg 1$, one thus finds (Scheuer and Readhead 1979)

$$\mathcal{P} \simeq \left(\frac{2S}{S_\perp}\right)^{-1/(2+\alpha)} - \frac{1}{2\gamma^2}, \tag{8}$$

for $S_\perp < S < 0.5(2\gamma^2)^{2+\alpha} S_\perp$. We shall see in § VI that this $S^{-1/2}$ distribution is completely inconsistent with the observations, so that at least one of the following must be false: A) all quasar jets have the same ratio of radio emissivity to optical luminosity, B) all quasar jets have the same velocity, C) all quasar jets are narrow, homogeneous, and all the emitting material in them moves with the same *vector* velocity. We explore the consequences of relaxing each in turn.

b) A Luminosity Distribution of Candles at Random Angle to the Line of Sight

We continue to assume that all the sources are narrow jets with identical velocities, but we now allow the jets to have a *distribution* of luminosities $n_\perp(L)dL$ when viewed from $\theta = \pi/2$. Then the number of sources per unit volume with *apparent* luminosity greater than L_a is

$$N_a(>L_a) = n_\perp(L > L_a) + \int_{L_a/A_{max}}^{L_a} \mathcal{P}(A(\theta) > L_a/L) n_\perp(L) dL \tag{9}$$

$\mathcal{P}(A > L_a/L)$ is given by equation (8) with $S/S_\perp$ replaced by L_a/L. Suppose that $n_\perp(L)$ is a broken powerlaw

$$n\perp(L) = fL_*^{r-1}L^{-r}, \quad L < L_* \tag{10a}$$

$$n\perp(L) = fL_*^{s-1}L^{-s}, \quad L > L_* \tag{10b}$$

where $f = (1-r)(s-1)/(s-r)$ gives unit normalization, and we must have $r < 1$ (to give a finite number of sources) and $s > 2$ (to give a finite total luminosity). Hence

$$N_a(>L_\alpha) \simeq ff_1\gamma^{(2s-2)(2+\alpha)-2}(L_a/L_*)^{1-s} \quad \text{for } L_a > 2^{1+\alpha}\gamma^{2(2+\alpha)}L_*, \tag{11}$$

where f_1 is a number of order unity. For $L_a > 2^{1+\alpha}\gamma^{2(2+\alpha)}L_*$, the sources are mainly maximally beamed ones (i.e. seen at angles $\theta \lesssim \gamma^{-1}$) and the luminosity function has the same slope as the unbeamed one, but with amplitude increased by the factor $\gamma^{(2s-2)(2+\alpha)-2}$.

For $L_* < L_a < 2^{1+\alpha}\gamma^{2(2+\alpha)}L_*$, the sources are predominantly those with $L \sim L_*$ seen at intermediate angles $\theta \sim (L_*/L_a)^{1/(4+2\alpha)}$, and the integral luminosity function

$$N_a(>L_a) \simeq ff_2(L_a/L_*)^{-1/(2+\alpha)} \quad \text{for } L_* < L_a < 2^{1+\alpha}\gamma^{2(2+\alpha)}L_*, \tag{12}$$

has the same slope that it would if all the sources had $L_\perp = L_*$; f_2 is a number of order unity.

For $L_a < L_*$ the sources are predominantly unbeamed, $L_a \sim L$, seen at angles $\theta \sim \pi/2$. The luminosity function is, up to factors of order unity, the same as equation (10a).

The observed integral source counts of flat-spectrum quasar cores (see § VI) have a slope of 1.5 at the bright end, and ~ 0.2 at the faint end. Interpreted along the above lines, this would require $s \simeq 2.5$, $r \simeq 1.2$ and $\gamma \lesssim 1.5$ [to avoid a significant range of apparent luminosities where the number counts vary as in eq. (12)]. Since the high apparent brightness temperatures and superluminal motions in some compact cores require $\gamma \gtrsim 5$, we deduce that if hypothesis (A) is false, then hypothesis (B) must also be false. Thus we are led to consider

c) Standard Candles with a Distribution of Speeds.

Since there is no reason to suppose that jets with different speeds should have the same emissivities, we suppose that the apparent luminosity at $\theta = \pi/2$ of a jet is some arbitrary function $L_\perp(\gamma)$ of its Lorentz factor, and consider a distribution $N(\gamma)$ of Lorentz factors. In general, one would expect a two-dimensional distribution $N(\gamma, L_\perp)$ with a range of $L_\perp$ at any given γ. We restrict ourselves to the case when the effect of the spread in $L_\perp$ is small compared to that of the spread in γ; the opposite limit was treated in the previous subsection.

To explore the consequences, let us suppose that $L_\perp(\gamma) = L_o\gamma^p$ and that $N(\gamma)d\gamma \propto \gamma^{-q}d\gamma$ for $1 \lesssim \gamma < \gamma_M$. Then defining $L_1 = L_o\gamma_M^p$ and $L_2 = L_o\gamma_M^{p+2(2+\alpha)}$, one finds that if $\sigma \equiv 1 - q + p/(2+\alpha) > 0$, then

$$N_a(> L_a) \simeq (L_a/L_o)^{-1/(2+\alpha)}\gamma_M^\sigma \qquad L_1 < L_a < L_2 \quad (13a)$$

$$N_a(> L_a) \simeq (L_a/L_o)^{\frac{1-q}{p}} \qquad L_o < L_a < L_1 \quad (13b)$$

while if $\sigma < 0$, then

$$N_a(>L_a) \simeq (L_a/L_o)^{-\frac{1+q}{p+2(2+\alpha)}} \qquad L_o < L_a < L_2 \qquad (14)$$

For all plausible values of p and q, the luminosity function is flat for high luminosities, in conflict with the observations (see below). Thus we deduce that if hypothesis (B) is false, then hypothesis (A) must be false too.

VI. LIES, DAMN LIES, AND BEAMING STATISTICS

Assume, for the sake of argument, that the optical line emission from quasars is equally detectable from all directions (this assumption is examined more closely below). Then an optically-selected ensemble of quasars will have their putative preferred axes oriented at random on the sky. To be definite, consider quasars with B-magnitude $m_B < 17.0$. The most complete optical surveys (Mitchell *et al.* 1984) find 0.09 such objects per square degree.

All-sky surveys of radio sources with flux at 5 GHz $S_{5000} \gtrsim 1$ Jy (Ulvestad *et al.* 1981; Perley 1982) identify $\sim 2 \times 10^{-3}\mathrm{deg}^{-2}$ or 2% of these quasars with compact, flat-spectrum ($\nu^{-\alpha}$, $\alpha < 0.5$) radio sources. The morphology of these sources is quite different from that of the "classical-double" 3C quasars. The median source in Perley's (1982) list has less than 1% of its flux at 1.4 GHz coming from regions more distant from the core than ~ 1" ($= 15h^{-1}$ kpc for a quasar at $z \sim 1$). Such resolvable structure as there is is usually in the form of asymmetrical blobs or convoluted corkscrews (Browne *et al.* 1982*a*; Perley it et al. 1982; claims by the first set of authors of diffuse halos with $\sim 10\%$ of the flux are disputed by the second set). The remaining 99% of the flux comes from a compact flat-spectrum core which is typically only slightly resolved (Zensus *et al.* 1984) at 5 GHz with an angular resolution of ~ 1 mas ($\sim 15h^{-1}$ pc for $z \sim 1$).

These morphological characteristics have led several authors (Scheuer and Readhead 1979; Blandford and Königl 1979;

Orr and Browne 1982) to suggest that there is a large population of quasars whose nuclei contain highly relativistic radio-emitting jets, and that the core-dominated flat-spectrum sources are merely those few oriented so that we have a view down the jet.

We have compiled data on the radio properties of quasars with $15.0 < m_B < 17.0$. The sources were the following: $S_{178} > 10$ Jy, Laing, Riley and Longair 1983; $S_{5000} > 1$ Jy, Perley 1982 and Ulvestad *et al.* 1981; $S_{408} > 0.5$ mJy, Condon *et al.* 1981. The integral counts at 5 GHz are presented in Figure 1.

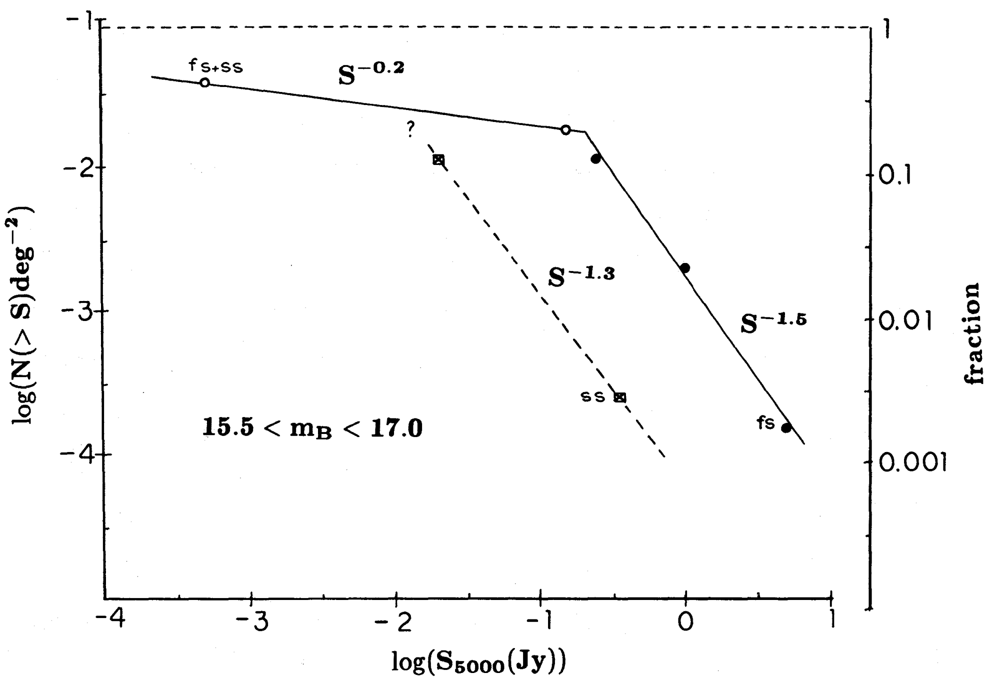

Figure 1. Radio luminosity function at 5 GHz of quasars with $15.5 < m_B < 17.0$. The filled circles are number densities of flat spectrum quasars. The crosses are number densities of steep-spectrum quasars. The open circles are detection fractions at 5 GHz (i.e. both flat spectrum and steep spectrum sources). The detection fractions have been put on a common scale with the number densities, assuming a total quasar number density of 0.09 deg^{-2}. See text for references.

The $N(> S_{5000})$ curve varies as $S_{5000}^{-1.5}$ for $S_{5000} > S_* \simeq 0.1$ Jy (corresponding to a radio/optical luminosity ratio $(\nu f_\nu)_{5\mathrm{GHz}}$

$/(\nu f_\nu)_B \simeq 4 \times 10^{-4}$), but flattens to $S_{5000}^{-0.2}$ for $S_{5000} < S_*$. The shape of the radio luminosity function is quite similar to the luminosity function of galaxies. The break in the luminosity function at S_* allows one to cleanly separate quasars into two subspecies: the radio-quiet ($S < S_*$) and the radio-loud ($S > S_*$). About 10% of quasars are radio-loud in this sense.

Figure 1 allows us to draw the following conclusions. If (as claimed by Browne *et al.* 1982*a*) flat-spectrum core-dominated quasars with $S_{5000} > 1$ Jy were surrounded by a diffuse, isotropically emitting halo whose flux at 1400 MHz was 10% that of the core (implying that the halo, with a spectral index ~ 1, would have $S_{5000} \sim 0.03$ Jy and $S_{408} \sim 0.3$ Jy), then the halos would have been detected in the survey by Fanti *et al.* (1975). If the flat-spectrum cores are beamed, then their unbeamed counterparts should have appeared as steep-spectrum quasars. Such objects are only three times more numerous than the flat-spectrum sources with $S_{5000} > 1$ Jy. Thus one must conclude that *either* *a*)the beaming is *very* broad (into ~ 2 steradian), or *b*) the optical line emission from quasars is very anisotropic and most of the 'unbeamed' couterparts of the flat-spectrum quasars are not normal quasars but a large population of red quasars (Beichman *et al.* 1981; Bregman *et al.* 1981), dusty radio galaxies, or empty field IRAS sources, or *c*) the 10% halos do not exist, or are relativistically beamed. If one accepts that the flat-spectrum core-dominated quasars with C($S \sim S_*$) are significantly beamed, then one is again forced to conclusion (*a*) or (*b*), whether the isotropic halos exist or not. The prescient paper by Strittmatter *et al.* (1980) derived (for fainter prism-selected quasars) a radio luminosity function similar to the one shown in Figure 1, and pointed out that its shape was quite inconsistent with the predictions of simple 'unified scheme' beaming models.

In §V, we showed that the shape was inconsistent even with slightly more complicated models. Thus at least one of the following must be true: 1) unbeamed quasars aren't classified as quasars; 2) there is no 'unified theory' and orientation is not the primary cause of the apparent differences between quasars; or 3) the emitting jet material is not smooth and homogeneous with a top-hat velocity profile. We suspect both 2) and 3), and thus discuss

VII. REALISTIC JETS

a) What Do We See?

We observe only synchrotron radiation. Synchrotron emission requires the presence of both magnetic fields and relativistic particles. Magnetic fields are amplified in shear flow. Shear flow occurs around obstacles, downstream of curved shocks, and near the boundaries of a jet. Relativistic particles are accelerated in shocks, by turbulence, and by diffusive pumping. It is thus to be expected that synchrotron radiation will be a tracer of the most dissipative (complicated and chaotic) regions of a flow.

If the flow is even mildly relativistic, the problem of diagnosing the flow from the observed emission is further complicated, since the motion greatly enhances the brightness of regions moving rapidly at small angles to the line of sight. For example, consider a large volume V_r of fluid at rest. Let it have some emissivity $j_\nu \propto \nu^{-\alpha}$. Suppose that inside this volume of stationary fluid is a small blob (volume V_m) of fluid with identical (rest-frame) emissivity, moving with speed βc at an angle θ to the line of sight to a distant observer. The ratio of the observed flux S_m from the small blob to that from the large volume of fluid at rest is

$$\frac{S_m}{S_r} = \frac{\gamma}{[\gamma(1-\beta\cos\theta)]^{3+\alpha}} \; \frac{V_m}{V_r - V_m} \, . \tag{15}$$

This simple result has rather stunning consequences: only one part in 10^3 of the fluid volume need move toward the observer with a Lorentz factor $\gamma = 2.8$ for it to dominate the observed flux. Only one part in 10^6 need move toward the observer with a Lorentz factor of 12.6 for it to appear more luminous than the other 99.9999% of the fluid! From the point of view of an observer with a line of sight at right angles to these, of the total flux only 0.008% will come from the blob moving with $\gamma = 2.8$, and only 0.0000002% from the blob with $\gamma = 12.6$.

In a real jet, shocks and instabilities will guarantee that fluid elements in the jet will have a rather wide range of speeds and directions of motion (cf. Norman *et al.* 1983; Blandford 1984; Lind and Blandford 1985). Our simple example illustrates the important point that *different observers will see different parts of a relativistic jet.* Unless the variations in emissivity between different parts of the jet are extremely large, most of the flux received by a given observer will have been emitted by those fluid elements which happen to be moving most rapidly towards him.

b) Bends and Wiggles

The interpretation of observations is further confused by the fact that in a time-dependent flow, streamlines (whose tangents are instantaneous velocity vectors), streaklines (paths of dye injected into moving fluid from fixed points), and particle paths are *not* the same. For example, a high-density (ballistic) jet whose nozzle is precessing or wiggling has *straight* particle paths, but wiggly streaklines. Relativistic jets must probably have densities much lower than ambient, and will therefore not be ballistic. Nevertheless, overly simple models of smooth jet flow in curved channels may make misleading predictions about the brightness variation in curved relativistic jets.

A jet of diameter h which is bent with radius of curvature R must have a proper Mach number

$$\mathcal{M} = \frac{\gamma_j \beta_j c}{u_s} \lesssim \sqrt{\frac{R}{h}}\,, \tag{16}$$

where $u_s = c_s/\sqrt{1 - c_s^2/c^2}$ and c_s is the internal sound speed. If the jet has a relativistic speed and a relativistic internal equation of state, then $u_s = c/\sqrt{2}$ and equation (16) becomes $\gamma_j \lesssim \sqrt{R/2h}$. A plane curve with true radius of curvature R_T will have an apparent (projected) radius of curvature $R_a \simeq R_T \sin^2\theta$ as seen by an observer whose line of sight lies in a plane which contains the tangent to the curve and the normal to the plane of the curve, with which plane the line of sight makes an angle θ (i.e. to an observer looking down the curved jet, except for a misalignment angle θ). The superluminal sources typically have $R_a \sim 4h$, so $\gamma_j\beta_j \lesssim 1.5/\sin\theta$. The statistics require $\theta \gtrsim 10°$; hence $\gamma_j \lesssim 10$. Notice that this is a limit on the Lorentz factor of the moving *fluid*; the apparent superluminal speed is determined by the speed of the emission *pattern* (§VII.*c*).

The brightness of a relativistic jet which seems to turn a sharp corner (i.e. bends with $R_a \sim h$) will not change significantly around the bend. In order to make the bend it must have $\gamma_j \lesssim 1/\sin\theta$. Its radiation will thus be beamed into an angle $\gtrsim \theta$. Since the true (deprojected) deflection angle is only $\sim \theta$, the brightness will change only slightly. Jets with gentler bends could show large brightness changes, if their flow were laminar, with a top-hat velocity profile. However, if 1) there are strong internal shocks (such as appear in the numerical simulations by Norman *et al.* 1983), or 2) the jet has a smooth velocity profile, then the jet will contain fluid elements moving with many different speeds and with velocity vectors covering a cone with opening angle much wider than $1/\bar{\gamma}$ (where $\bar{\gamma}$ is some mean Lorentz factor). In case 1), the jet might appear 'knotty'; in case 2) it would appear slightly edge-brightened.

c) What's Changing? -Superluminal Motion

As was first pointed out by Rees (1967), a source of photons moving with a speed close to the speed of light will, to some observers, appear to be moving across the sky with a speed exceeding the speed of light.

Consider a source of photons which at time $t = 0$ lies at

$x = 0$ and emits photon 1 in the direction of an observer at some very great distance D, at an angle θ to the x-axis. See Figure 2.

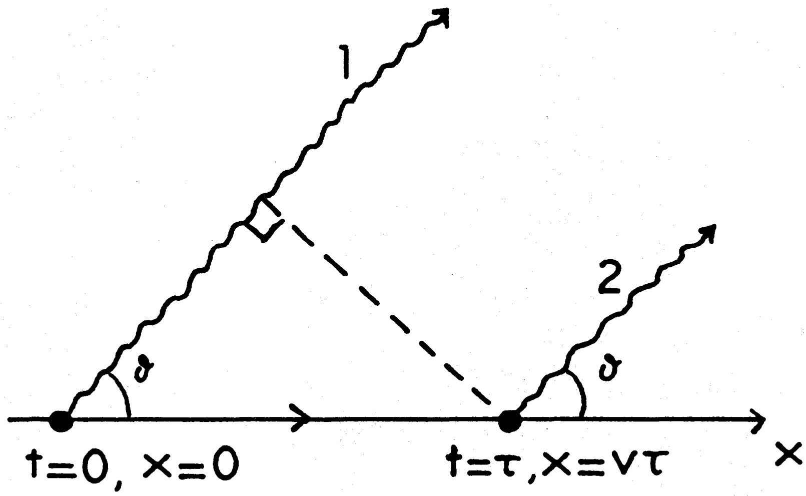

Figure 2. Superluminal motion.

At a later time τ the source is located at $x = v\tau$ and emits photon 2, also in the direction of the distant observer. This observer will receive photon 1 at time $t_1 = D/c$ and photon 2 at time $t_2 = \tau + [D - v\tau\cos\theta]/c = t_1 + \tau(1 - \frac{v}{c}\cos\theta)$. If $v > c$, observers at angles $\theta < \cos^{-1}(c/v)$ will receive photon 2 *before* photon 1. This is how tachyons wreak havoc with causality. There is, however, no objection to non-material sources of photons moving with velocities $v > c$. For example, let the x-axis be surrounded by some material able to scatter light (a white ribbon, or an electron-scattering jet). If a plane-wave pulse with wave-front normal velocity $v_w = c$ moves across this material at an angle α, then the source of scattered photons moves along the x-axis with a velocity $v_w/\cos\alpha > c$. See Figure 3. For α sufficiently close to 90°, even subluminal ($v_w < c$) wavefronts —e.g. shock waves— can produce regions of excitation moving with superluminal velocities.

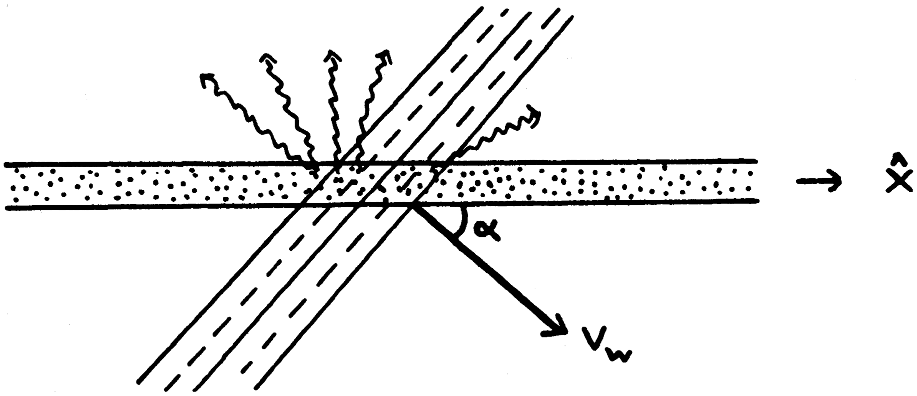

Figure 3. Scattering screen.

Return now to Figure 2. The distant observer will see the source of photons moving across the sky with an apparent velocity $(v\tau \sin\theta)/(t_2 - t_1)$:

$$v_{app} = \frac{v \sin\theta}{(1 - \frac{v}{c}\cos\theta)} . \tag{17}$$

For $v = c\sqrt{1-\gamma^{-2}}$, v_{app} is maximized for observers at $\theta = \sin^{-1}(1/\gamma)$, who see $v_{app} = \gamma v$. Notice that the photons which reach these observers must be emitted perpendicular to the x-axis as seen in a frame moving with the source. Hence if the source is a plane sheet with normal along the direction of its motion (e.g. a perpendicular shock front), it will appear *edge-on* to those observers for whom it has the greatest apparent velocity.*

If $v < c$ all observers will agree on the direction of the photon source's motion. But if $v > c$, some observers will see the source moving backwards. For example, in the simple scattering-screen model illustrated in Figure 3 ($v = c/\cos\alpha$) observers at angles $\theta < \alpha$ will see the illuminated spot moving in the $-\hat{\mathbf{x}}$ direction. The traditional argument against such screen models

* Recall that an object in relativistic motion is *measured* by a lattice of observers to be contracted but unrotated, yet to a single observer *looks* rotated but uncontracted.

has always been that the sources observed with VLBI exhibited only superluminal expansion, never contraction. Recent tentative reports of superluminal contractions in 0711+356 (Readhead *et al.* 1984) and in 4C39.25 (Shaffer 1984) suggest that things may not be quite so simple. It is nevertheless still the case that all of the well-studied sources with convincing evidence for superluminal motion show *only* steep-spectrum blobs moving *away* from the flat-spectrum core (—which in 3C 345 is now known to be at rest on the sky —Bartel *et al.* 1984).

The interpretation of these phenomena is unfortunately complicated by the fact that the observed properties of a source of waves depend not on one, but on several velocities:

- c, the speed of propagation of the observable radiation.
- v_{em}, the physical velocity of the material *em*itting the radiation.
- v_p, the velocity at which the *p*attern of emitting material moves.
- v_s, the velocity of propagation of the *s*ignal which excites the pattern.

These all interact to produce

- v_o, the *o*bserved apparent velocity of some identifiable feature.

The importance of distinguishing these velocities [emphasized by Blandford, McKee and Rees (1977)] is best illustrated by a simple example. Consider a line of taxi cabs of length ℓ waiting at a red light at an intersection. When the light turns green, an exciting signal propagates down the line at velocity v_s = 186,000 miles s^{-1}, until it reaches the first taxi driver in a bad mood. After a time τ (the reaction time of a typical taxi driver), he honks his horn. This infuriates the driver in front, who (after a time $\frac{\ell}{c_s} + \tau$) honks his horn, and the process repeats itself. Clearly $v_{em} = 0$. The wave of honks however, propagates up the line of cabs at a velocity $v_p = \left(\frac{1}{c_s} + \frac{\tau}{\ell}\right)^{-1}$, [where c_s is the speed of sound]. As heard by a distant pedestrian at an angle θ to the line of cabs, the honk-front seems to be running forward at a velocity

$$v_o = \frac{c_s \sin\theta}{(1 - \cos\theta) + \frac{c_s \tau}{\ell}} . \tag{18}$$

If $c_s\tau/\ell < (\sqrt{2}-1)$ [i.e. if the drivers' reaction time $\tau < 0.007(\ell/20$ ft) s], the honk-front can seem to propagate forward supersonically. Of course, there will be no sonic boom (the "beaming" phenomenon normally associated with supersonic motion), since it is only the wave of fury which is propagating forward, not the individual horns. In this example, as probably in real compact radio sources, all five velocities are physically and numerically distinct. In particular, notice that if there is a coupling between particles capable of emitting, it is very easy to excite a wave of excitation that can propagate at a velocity v_p quite different from v_{em} [this decoupling of v_p and v_{em} also occurs in screen models where the pattern of excitation is determined by an external signal]. Superluminal motion does not imply beaming, nor does beaming necessitate superluminal motion.

We now exhibit two physically reasonable mechanisms whereby a source can exhibit superluminal expansion, yet appear equally bright as seen from a range of angles as wide as a steradian. They make quite different predictions regarding the incidence of superluminal motion.

i) Sonic Booms

Suppose that the fluid in a compact radio source usually moves with nonrelativistic speed. If a "bullet" (which could be an intense stream of fluid) is fired through it with relativistic speed, it will be surrounded by a relativistic bow shock. The structure of such bow shocks is not difficult to determine with similarity techniques.

If the bullet is more-or-less spherical, of radius R and moving with Lorentz factor γ_b, then at a distance z downstream of the bullet the shock is found to have a transverse extent $r \simeq (Rz)^{1/2}$). In the shock-frame the shock-normal component γ_n of the incoming fluid's Lorentz factor (which determines the downstream pressure $p \sim \rho_e c^2 \gamma_n^2$) is $\gamma_n \simeq \gamma_b (R/z)^{1/2}$. The paraboloidal shock is thus relativistic to a distance $\sim \gamma_b^2 R$ downstream, where it has a transverse extent $\sim \gamma_b^2 R$.

If we piously assume that relativistic particles and magnetic fields are always in equipartition, with pressure proportional to the pressure downstream of a shock, then the local synchrotron emissivity $\propto p^{7/4}$. Adding up the Doppler-boosted emission from all the fluid elements downstream of the shock, one finds that the flux S from the bowshock of a spherical bullet varies as $\theta^{-1.5+\alpha}$. The emission is much less beamed than the emission from a spherical plasmoid, $S \propto \theta^{-(6+2\alpha)}$, θ being the angle between the observer's line of sight and the direction of bullet motion. If $\alpha = 0$, the resulting $P(> S) \propto S^{-4/3}$, quite close to the slope observed for radio-loud quasars (Section VI). A naïve unified scheme of such bullets would thus predict $P(> S) \propto S^{-4/3}$ for $S > S_*$, and $v_o/c \simeq (S/S_*)^{2/3}$, where $S_* \simeq 0.3$Jy for quasars of apparent B magnitude ≈ 17 (*cf.* section VI).

Such predictions should not be taken too seriously. Repeating the calculation for the cylindrical bullet, one finds that the emission is now dominated by the nonrelativistic edges of the bow shock, so that S is nearly independent of θ. Achterberg (1984) has given reasons to suppose that a highly relativistic shock may be an inefficient accelerator of ultrarelativistic particles; if this is true, the flux from the bowshock of a spherical bullet could be independent of θ as well. In either case a completely unified scheme would not be possible. The observed superluminal velocity would not be a unique function of flux (which would have to depend on intrinsic parameters), and the fraction of objects of a given flux exhibiting apparent velocities in excess of v_o would be $\sim (c/v_o)$ for the cylindrical bullet, and $\sim (c/v_o)^2$ for the modified spherical bullet.

ii) The End of a Shock Tube

We have seen that flow with curved shocks are both plausible and sufficiently flexible to explain almost any observations of superluminal motion. There exists, however, a second equally plausible class of flow models that Scheuer, in his delightful (1984) review, named 'computer-controlled Christmas-trees with beamed lights.' In these models, emitting fluid elements in an initially plane pulse are made to travel relativistically along diverging trajectories. A distant observer sees a bright spot at the projected position of the elements which are moving directly towards him. As the emitting surface expands and distorts, the spot will move. Superluminal velocities are visible from a very wide range of angles, which mitigates the problem of the excessive deprojected sizes of superluminal sources (Schilizzi and de Bruyn 1983). If a variation in the central engine sends a relativistic shock up a pre-existing pressure-confined jet that becomes free at some radius, then when the shock reaches this point it will rapidly balloon outwards, and a 'computer-controlled Christmas-tree' will have been born.

Given our ignorance of the detailed structure of the flow of plasma in compact radio sources, we can conclude only that curved relativistic shocks are likely to be present, and that they can plausibly explain almost any statistical statement about fluxes and the incidence of superluminal motion. Progress requires better observational diagnostics. One of the best is polarization, especially when coupled with high-resolution mapping.

VIII. POLARIZATION —SYSTEMATIC OR STOCHASTIC?

a) The Facts

The polarization of a source, being a mapping from a line (time) onto a plane [the Stokes' parameters $(Q(t), U(t))$], contains infinitely more information than its intensity, which is merely a mapping from a line (time) onto a line $[I(t)]$. It is an important diagnostic of anisotropy in sources (or components of sources) which we are not yet able to resolve.

The efforts of Rudnick, Jones and collaborators (Rudnick *et al.* 1985) have at last provided, for more than a dozen compact sources, multi-frequency observations of all three Stokes' parameters well-sampled in time. The sources are linearly polarized, with polarizations of a few percent.* In most core-dominated sources the headless polarization vector is the sum of a random component and a steady component. The steady component is usually perpendicular to the source major axis seen on VLBI maps (which axis is only poorly correlated with the source axis on the 10kpc scales resolved by the VLA). The root-mean-square length of the random component of the polarization vector is comparable to the length of the steady component.

Recent advances in observational technology have made it possible to make VLBI maps of polarized as well as total flux. Preliminary results for two objects —3C454.3 (an OVV quasar; Cotton *et al.* 1984) and OJ 287 (a BL Lac object; Roberts *et al.* 1984) indicate that the source is resolved into a low-polarization flat-spectrum core and a more highly polarized steep-spectrum "jet." In the core the polarization **E** vector is parallel to the source major

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* Sporadic reports of circular polarization at the level of 0.3% have not been universally confirmed. Recent measurements of circular polarization are reported by Komesaroff *et al.* 1984, who also discuss its standard interpretations. A convincing measurement of *large* circular polarization at high frequency would indicate the presence of coherent radiation mechanisms.

axis; in the "jet" it is perpendicular. This is qualitatively what one would expect near the photosphere of a synchrotron source with its magnetic field predominantly along the source axis: the jet is above the photosphere, so the source is optically thin and the radiated **E** vector is perpendicular to **B**; the core below the photosphere is optically thick, so the radiated **E** vector is *parallel* to **B** (since this polarization component has a much longer mean free path to absorption). There are, however, quantitative difficulties with this explanation, so there may be a real difference in the field structure between core and jet. Improved observations will be of great interest.

The results tend to confirm the expectation that most of the polarized flux from flat-spectrum cores comes from that (outer) part of the source which is optically thin at the observing frequency.

The time dependence of the polarization in most sources most of the time seems best described as a random walk in the $Q-U$ plane (Moore *et al.* 1982; Rudnick *et al.* 1985; Jones *et al.* 1985). The picture is confused by a few isolated events (of which the cleanest is still the famous outburst of AO 0235+164 —Ledden and Aller 1978) in which the polarization position angle changes smoothly and monotonically.

b) The Pictures

The aberration of light causes an accelerating fluid element to appear to rotate as seen by a distant observer (Terrell 1959). If the observer's line of sight makes an angle θ with its direction of motion, then for $\gamma < \operatorname{cosec}\theta$ the observer will be looking at the front side of the element; for $\gamma = \operatorname{cosec}\theta$, she will see it as if perpendicular to its direction of motion; for $\gamma > \operatorname{cosec}\theta$ she will see the back side. If the fluid element has a magnetic field which is symmetric (though this may be only in a turbulent way —*cf.* Laing 1980) about some axis which is *not* parallel to the direction of motion, then the rotation in viewing angle due to the acceleration will cause the **E** vector of the polarized radiation to rotate. The total angle of rotation can evidently not exceed π. Blandford and Königl (1979) proposed this phenomenon as an explanation of the smoothest part of the rotation in position angle seen during the outburst of AO 0235+164. The total rotation in this event (as in a few other reported cases: Aller *et al.* 1981) exceeded π, however, so the relevance of the explanation is questionable.

A second physically interesting mechanism can explain rotations in PA exceeding π. A helix is formed by uniform translation of a uniformly rotating vector. A shock propagating down a jet's axis will illuminate successive cross-sections. *If* the largest component of a jet's magnetic field were to be a simple global helical field, and a shock were sent down its axis, then to an observer whose line of sight made an angle $\theta \ll 1/\gamma$ to this axis, the electric vector of synchrotron radiation from particles near the shock would appear to rotate smoothly as the shock propagated down the helical field. A specific example of this idea has been worked through by Königl and Chaudhuri (1985). Notice that an observer will see a rotation only if her (aberrated) line of sight lies inside the cone defined by the pitch angle of the helix.

Such smooth rotations as that in AO 0235+164's outburst seem, however, to be very infrequent, and even in this otherwise well-behaved event the intensity of the polarized flux varied wildly while its position angle changed smoothly. As discussed in the previous subsection, the polarization more commonly performs a seemingly random walk in the $Q-U$ plane. Since a random walk can occasionally and accidentally behave regularly, infrequent regularities in the polarization might be suspect.

The polarization would be expected to make a random walk in the $Q-U$ plane if the observed flux came from several subregions whose relative intensities changed in an uncorrelated way (Moore *et al.* 1982). The intensity changes could be caused either by actual changes in the emissivity of the subregions, or by the beaming of their radiation in different directions as their (relativistic) velocity varied. Accelerating a blob whose magnetic field is neither turbulently nor truly symmetric about a preferred axis causes similar behaviour (Björnsson 1982). The regularities in the otherwise chaotic sea of polarizations are potentially of such great physical importance that it would be comforting to know that they cannot be mere statistical flukes. Jones *et al.* (1985) have made a first attempt at determining the frequency of rotations in random walks. Their work inspired the author to make a slightly more detailed investigation. It is hoped that it will in turn inspire someone with a large body of observational data to determine the statistical significance of 'rotation events.'

c) Drunken Lucidity

The polarization 'vector' is not a vector but an indirection (a headless vector; see Kendall and Young 1984 for the coinage). The essential features of the statistics of indirections were recognized only a few years ago (Kendall and Young 1984; Kendall 1984).

To simplify the topology, we work not with the position angle χ, but with the angle $\theta = 2\chi$ in the $Q-U$ Stokes' parameter plane. A 180° swing in PA thus corresponds to a rotation of 360° about the origin of the $Q-U$ plane. We define a PA swing through an angle $\chi_{\rm rot}$ as a rotation event if θ rotates "almost monotonically" through an angle $\Theta_{\rm rot} = 2\chi_{\rm rot}$. "Almost monotonically" means that a temporary change in the direction of swing of the vector should not carry it back by more than some predetermined angle Θ_{al} (which an observer might take to be of order the measurement error or some subjectively allowed 'background jitter'). We say that the swing is 'smooth' if between observations θ does not change in *either* direction by more than Θ_{al}.

Our hypothesis is that the polarization of the source is the sum of some large number N of random vectors whose directions change randomly on a timescale T. The lengths of the vectors are assumed constant, but the results are not significantly different if the lengths are chosen from some distribution with a non-

TABLE 1

Probabilities of Rotation Events

$\Theta_{\rm rot}$	Θ_{al}	P_{sim}	P_{pred}
360°	90°	0.05	0.08
360	60	0.025	0.03
360	45	0.013	0.010
360	30	0.0012	0.0009
720	90	0.002	0.005

zero mean. We ask: after a time t, how many events will have been observed in which the polarization vector rotates smoothly and almost monotonically through an angle $\Theta_{\rm rot}$? To order of magnitude, this is equivalent to asking for the probability that in $n = \Theta_{\rm rot}/\Theta_{al}$ coin tosses we obtain either all heads (clockwise rotation) or all tails (counterclockwise) —namely $2^{-(n-1)}$. The time between coin tosses is of order $\Theta_{al}T$. Hence in time t, we will see about

$$2(t/T)\Theta_{al}^{-1}2^{-(\Theta_{\rm rot}/\Theta_{al})} \tag{19}$$

events. The essential correctness of this result has been verified by Monte-Carlo simulation. Representative results are summarized in Table 1, which gives the probability P_{sim} of a rotation event per unit polarization decorrelation time T. P_{pred} is the probability predicted by the simple argument (VIII.1), which works surprisingly well. Recall that $\Theta_{\rm rot}$ and Θ_{al} are *twice* the corresponding PA's.

Ledden and Aller's observations of AO 0235+164 have errors in PA of the order of 15°, so $\Theta_{al} \lesssim 30°$. Such events, if accidental in a random walk, should occupy only 0.12% of the monitoring time. The event lasted about a month. Thus, if subsequent well-sampled monitoring showed that similar events occurred with a frequency much higher than once every 50 years, there would be a convincing case for their physical origin (especially if the rotations always coincided with flux outbursts!). The probability of accidental rotation events becomes exponentially small as Θ_{al} decreases. If the events remained smooth and monotonic with observational precisions of 5° in PA, little doubt could remain.

The data required for such a statistical test may already exist. By way of encouragement, we point out that at the midpoint of the polarization swing during the outburst of AO 0235+164 (Ledden and Aller 1978) the polarized flux suddenly peaked. A pessimist would note that the first (and only examined) of 49 successful simulated swings (in 40,000 correlation times) with $\Theta_{al} < 30°$ shows a very similar feature. An optimist would note that this is what would be expected if the emission came from the bow shock upstream of an obstacle being accelerated by the jet (the turbulent magnetic field having been there compressed into a two-dimensional sheet). As the quality of VLBI polarization maps improves (Cotton *et al.* 1984), they will become a powerful diagnostic of events in compact radio sources. If the optimist is correct, these may have easily legible signatures.

IX. THE FUTURE

Two decades of hard work have taught us painfully little about the physical nature of central radio sources. The phenomenology is now much richer; simple toy models can be ruled out. Yet we remain woefully ignorant of the processes that cause the radio sources to appear as they do. Almost none of the ingredients required for a quantitative model have yet been assembled. Still, even without a detailed understanding of their structure, central radio sources can be used as probes of conditions in the nuclei of galaxies, and as indicators of violent transformations of jets. For this reason, the greatest progress in the next decade will probably be in understanding the physical differences between radio cores. These can be due both to differences in luminosity and velocity between jets, and to differences in the density and distribution of gas in the nuclear regions. Already there are indications that these depend upon galaxy type and upon redshift (§II).

As regards the subject of this review: the actual structure of the central radio sources, the future seems less rosy. There are, however, a number of well-defined observational programs which would help to clarify our murky view:

- Observations of polarization at low frequencies. It is possible (§III) that low frequency variability is due entirely to refractive lensing by irregularities in the local interstellar medium. Such lensing cannot alter the direction of polarization of radiation from a single point source. A simple source should therefore preserve its polarization PA while its intensity varies (Blandford, private communication). Unfortunately we already know (§VIII) that sources are made up of at least two components with orthogonal polarization, only one of which is small enough to be lensed. In this case lensing will cause the angle of total polarization to change. The observational test is thus not entirely clean, but would still be of interest to try.

- VLBI at high resolution and high dynamic range (using QUASAT and the VLBA) will probably reveal source structure as complicated as that seen by the VLA in extended radio sources. Regularities could be diagnostic. If the flux outbursts are caused by obstacles entering the jet, one would expect the new component to have a sharp edge on the side closest to the nucleus (as seen in VLA maps of Cen A on a scale of 700pc —Burns *et al.* 1985). If the outbursts are due to increases in the jet's velocity (i.e. to shock waves propagating down the jet), the new component would have a sharp edge on the side furthest from the nucleus (like the sharp edges on the lobes of extended double radio sources).

- VLBI mapping in polarized flux will identify regions of large shear and help to define streamlines. Large-scale radio sources are static, but central radio sources vary in our lifetimes. With the aid of this additional dimension, it may be possible to use polarization observations to deduce viewing angles and thus the three-dimensional velocities —something we are still unable to do for extended radio sources! Mapping in polarized light should also clarify

- Swings in polarization angle. One of the few regularities in a sea of chaos, their statistical significance in still unclear. Their reality will be proven if they can be shown to be both smooth and common (§VIII). Their interpretation will depend upon whether they are correlated with flux outbursts, and upon how the percentage polarization varies as its PA swings (models here make quite definite predictions). High resolution mapping, in both polarized and unpolarized flux, would identify the moving parts.

- Multifrequency observations and mapping of a large sample of quasars selected by their optical emission lines (e.g. all those in a given redshift and magnitude range) are necessary to determine to what extent there are physical differences between their radio cores. Correlations between radio, X-ray, and optical line properties are a further (but not unambiguous) indicator.

The structure of central radio sources is probably complicated and rather uninteresting. The sources are of interest not so much *per se* as for what they represent: relativistic motion and the traumatic interaction of a jet with the interstellar medium of a young galaxy.

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APPENDIX
GALACTIC WEATHER FORCASTING

It is often stated —especially in funding requests and observing proposals— that further observations of radio sources or emission lines will reveal the secrets of the "central engines" which power active galaxies. This is no more likely to be true than the statement that further study of the earth's weather will suggest a solution to the solar neutrino problem.

Of course, radio sources and emission lines would not exist without the central engine; neither would the earth have weather without the sun. The things to calculate in cloud and jet models are the velocities and mass fluxes; everyone wishes that meteorological models would predict the wind velocity and the mass flux of condensed water in the neighborhood of their world lines.

Yet in gross average, the latter are easy to compute: a fraction f (of order unity) of the solar flux ($\sim$ 2 calories cm^{-2} min $^{-1}$ at earth) is absorbed in the atmosphere, in the topsoil (which heats the air by conduction) and in evaporating water (which releases its heat when it condenses). The power dissipated per unit area by a large turbulent eddy of characteristic wind velocity v_w is $\rho_{air} v_w^3$. This power cascades through smaller and smaller scales until molecular viscosity converts it into heat. The heat is radiated into space by collisionally excited molecular rotation transitions. In steady state the heat lost must balance the power absorbed. Hence $v_w \sim (fF/\rho)^{1/3} \sim 14 f^{1/3}$mph, as observed. Likewise, the latent heat $L = 590$ cal gm^{-1} released by the condensation of evaporated water must in steady state be replaced by the flux of solar energy absorbed by evaporating water $\lesssim (1-a)(.75)(.25)F$, where $a = 0.32$ is the albedo of the earth, 0.75 is the fraction of the surface covered by water, and the factor $0.25 = \frac{\pi r^2}{4\pi r^2}$ accounts for the fact that the sun shines only during daytime, while rain can fall at all hours. Hence the globally averaged rate of precipitation should be $\lesssim 0.125F/L \simeq 90$ inches yr^{-1}, also in reasonable accord with observation.

These results —charming confirmation that the sun is indeed the central engine driving the earth's weather— are diagnostic of nothing but the solar constant F and the density of the earth's atmosphere —as emission-line clouds are diagnostic of nothing but the ionizing flux and the cloud densities. To learn something else about the sun (or central engine) one must look elsewhere —for example, at the tides (or line profiles). Since the moon's effect on the tides is twice as great as the sun's, yet they have exactly the same angular size, one can immediately deduce that the mean density of the sun is half that of the moon —rather as one might use (with less physical justification) the virial theorem to deduce the mean density interior to a line-emitting region.

It may be instructive and humiliating for those confident that we can understand the two-phase equilibria of line-emitting clouds or the state of the non-thermal gas in radio jets to contemplate the problem of calculating the phase equilibrium of H_2O on a planet with atmospheric pressure 10^6 dyne cm^{-2} illuminated by a body ("sun") with $T_{eff} = 5900°$K and angular diameter 1/2°. If the planet were flat, non-rotating, black, insulating and normal to the "sun," it would have a temperature of 390 K, and the water would all be vapor. If the planet were spherical, black and rapidly rotating, it would have a temperature of 276 K, and the water would be mostly liquid, with some vapor. If the planet were spherical with an albedo of 0.32 and rapidly rotating, it would have a temperature of 250 K and the water would mostly be ice. If this latter planet had an atmosphere of molecules transparent to radiation with a color temperature of 5900 K, but with a Kramers' optical depth ~ 0.5 to radiation with a color temperature of 300 K

($\lambda \sim 10\mu$), it would have a temperature of 300 K, and the water would be liquid. On the other hand, dust grains with radii $\sim 1\mu$ would take a time $\sim (r/1\mu)^{-2}$yr (computed from Stokes' formula for viscous drag on a sphere on density 2 gm cm^{-3}) to settle out of the stratosphere. On a planet with radius 6700 km, only 1.5×10^9 tons (= 1 km^3, packed) of such dust would form a screen opaque to 5900°K radiation, but transparent to 300°K radiation, thus reducing the temperature of the planet to well below the freezing point of water. To lift the dust would require only $Mgh \sim 150(h/40$ km) Megatons of energy; keeping it continually suspended would require a mere 3×10^{-8} of the solar constant F.

To an observer on a planet orbiting α Centauri, the earth would have a magnitude at 10μ of ~ 23, comparable to that of a faint quasar. He could, from spectroscopy, deduce the pressure and composition of the earth's atmosphere. But would he predict the presence of liquid water (or for that matter, can *we*? Things were different in 1816; they may have been different for the dinosaurs; they may change again in our lifetimes)? And would he understand the strange non-thermal radio-emission; the occasional bursts of γ-rays?

No meteorologist would claim that study of El Niño, clear air turbulence or the growth of snowflakes will teach us anything about the solar interior. Yet the earth's weather is a fascinating subject; laymen love to talk about it, despite the fact that the underlying physics is so difficult and subtle as to have attracted —and stumped— many of the greatest minds in classical physics. We should take the phenomenology of active galaxies in the same spirit.

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