OBSERVATIONS OF GALACTIC AND EXTRAGALACTIC JETS

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I) INTRODUCTION

Since nearly all discrete radio sources of astronomical interest are of insufficient angular extent for their detailed structural properties to be accessible to single-dish radio telescopes, radio interferometry must be employed to gain information on the morphologies of these objects. Recently constructed imaging interferometer arrays which employ the technique of Fourier synthesis, particularly MERLIN and the VLA (Very Large Array), and the more recent VLBI arrays, have given unprecedented imaging capabilities, with the result that our knowledge, and hence perceptions, of discrete radio sources have vastly changed over the last few years. An equally important parallel development has been image processing algorithms. These have vastly improved the quality of information produced by these arrays, so that an instrument such as the VLA can now produce images with speed and quality exceeding original design specifications by factors of 100 to 1000.

In this contribution, the current state of observations of the phenomenon of radio jets, both galactic and extragalactic is reviewed. Although the bulk of the observations are from radio wavelengths, optical and X-ray data will be used where available. Due to space considerations, only a cursory review is possible and, since the following two talks will deal with interpretation, the review will be concerned almost solely with the data. Readers wishing more detail should consult the recent review articles by MILEY [1], on the structure of extended extragalactic radio sources; by BRIDLE and PERLEY [2], on extragalactic jets; and by KELLERMANN and PAULINY-TOTH [3], on compact radio sources. The theory of extragalactic jets is reviewed by BEGELMAN, BLANDFORD and REES [4]. The proceedings of two recent workshops [5,6] are also recommended.

The review begins with stellar jets, but as the majority of the available data concerns extragalactic jets, the bulk of this paper will be concerned with this phenomenon. For these, I will start with a description of the overall morphology of extragalactic radio sources, whose scales can exceed 1 Mpc, and work towards the pc scales accessible with VLBI techniques. Although this range of 1 million is impressive, it is still far less than the 12 orders of magnitude on which the extragalactic jet phenomenon is expected to operate over, as described by Roger Blandford in his review talk. Thus the physics of the central engine lie far inside those scales currently accessible to direct observation.

II) STELLAR JETS

Jets, or features which are suggestive of jets, are being found with increasing frequency amongst members of two very different classes of stellar objects. The first, protostellar objects, has been reviewed by Reinhart Mundt in the first talk of this Colloquium. As noted by him, these jets are associated with pre-main sequence objects, notably T-Tauri stars, and are found through Ha searches of star-forming regions. These jets are supersonic, and have lengths of typically .01 to .2 pc, opening angles of 3 to 10 degrees, and velocities of 50 to 400 Km/sec. Their termination or deflection points are suspected of being Herbig-Haro (HH) objects, which are thus explained in terms of shock heating from deceleration of the flow. Many of these jets are found in the same regions as bipolar molecular outflows [7], and it seems probable that a close relation exists between these phenomena. A recent review by LADA [8] is recommended.

The second class of stellar jets is associated with late-type objects. Most suspected or known jets in this class are X-ray sources, and their observational parameters have been recently reviewed [9], and are summarised:
a) SS433. This most interesting object, a binary system with 13-day period, has been the object of intense observational efforts since the discovery of the extraordinary, time-variable Doppler shifted Balmer and He I emission lines. The observations have been reviewed by MARGON [10]. The widely accepted kinematic model employs oppositely-directed twin gas jets of velocity 0.26c which precess with a period of approximately 164 days with half-angle of 20 degrees about a central axis inclined by 79 degrees to the line of sight. Both the optical and radio data are fitted excellently by this model. The arcsecond scale radio maps [9,11] show projected corkscrews with knots whose motion appears to be purely ballistic. There is no apparent evolution of the spectral index, \( a \), (defined as \( \log I = \text{const} + a \log v \)) of -0.6 to -0.7, and no depolarization down to 20 cm wavelength. No attempt to measure the rotation measure (RM) has yet been made, hence the intrinsic magnetic field directions are unknown. The blobs' apparent motion of 3" per year allow independent estimates of the velocity, and give a firm distance estimate of 5.5 Kpc [12].

b) Cyg X-3. Flux density measurements of this object, which is a binary with 4.8 hour period, but whose identification is uncertain, show violent flares [13]. Recent radio observations [14,15] show evidence of rapid (~0.1c), one-dimensional expansion on sub-arcsecond scales. The small angular size (~0.1 arcsec) prevents detailed tracking of the structure, so the evidence that this object is a jet is weak, but promising.

c) Sco X-1. This object is an extragalactic look-alike, with a core and pair of compact knots [16]. Recent VLA observations [17] show that the entire source is moving southward at 70 km/sec. The northern hotspot is moving radially outward at 35 km/sec, relative to the core. The southern hot spot is weaker, and an upper limit to its expansion velocity is 70 km/sec. Arguing by analogy with extragalactic sources, it seems likely that a relativistic jet is present [16], although there is no direct observational evidence of one.

d) CH Cyg. This object is a symbiotic star, and the evidence for a jet is fairly good, being presented in a contributed paper to this Colloquium by Taylor and Seaquist. They derive outflow velocities ~1000 Km/sec. Another symbiotic star, R Aquarii, has elongated structure seen in the radio, optical, and near-uv, which may represent a jet.

III) EXTRAGALACTIC JETS

Amongst the first objects observed with the newly constructed VLA were those radio galaxies and quasars which showed evidence of elongated structures from lower resolution maps. On theoretical grounds, the most luminous radio galaxies and quasars are expected to be resupplied on a quasi-continuous time scale [18,19], one means of which could be by a highly collimated supersonic flow, or jet [20]. The increased sensitivity and resolution that modern instruments provided over earlier ones soon revealed jets in a large proportion of extragalactic sources; the number of known jets (defined by the criteria in [2]) is now 143 [21], with at least 80 more that probably will join the list when better data are taken.

1) EXTENDED SOURCES

I discuss here the morphological characteristics of extended extragalactic radio sources. Since virtually all extragalactic sources show extended structure, the definition of an extended source is here made to specify lobe-dominated sources - those whose flux density is dominated by optically thin emission with spectral index (\( a \)) of -0.6 to -0.9.

a) Large-Scale Structure At low resolution, virtually all extended extragalactic sources show collimated, bilateral symmetry about a line which passes near the optical identification, if known. Both structural extent and brightness show symmetry, these can be used to place an upper limit to the bulk velocity of advance of ~0.1c of the extended regions [22,23].

There is a striking correlation between morphology and radio luminosity [24]. Those sources with 1400MHz spectral powers exceeding ~10^{25} W/Hz are edge-brightened, with regions of intense emission (known as hot spots) at the extremities, and generally linear morphology, while the weaker sources are more diffuse, more distorted, and without hot spots. These differences are illustrated in the following three figures representing distinct morphological categories. Fig. 1 shows the