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A Study of Mechanisms Producing Astrophysical Jets

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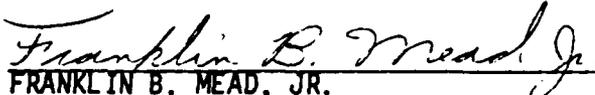
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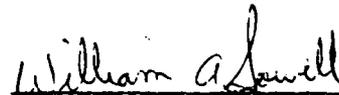
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FOREWORD

This final report was submitted by Innovative Systems, Ramey, PR, on completion of Small Business Innovative Research contract F04611-87-C-0048 with the Air Force Astronautics Laboratory (AFAL), Edwards AFB, CA. AFAL Project Manager was Dr Frank Mead.

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TABLE OF CONTENTS

INTRODUCTION	1
Defining Jets	1
STELLAR AND GALACTIC JETS	4
Galactic Jets	4
Stellar Jets	5
TIME SCALES OF JET PHENOMENA	6
Galactic	6
Stellar Systems	7
SOME CURRENT JET ACCELERATION MODELS	8
COMPARISON WITH OBSERVATIONS	9
QUESTIONS AND PUZZLES	10
A Note on the Cosmological Distance Assumption	10
How do we know it's a push and not a pull?	10
Problems with the Statistics of Jet Sidedness	11
QUESTIONS FOR INVESTIGATION	11
What sort of systems are ejecting the H-H sources?	11
Is there a disk in the crab?	11
Does a jet exist in SN1987a ?	12
Possible Secular Changes in the Vir A Jet	12
The Question of Material Motion Along the Jet	12
A TWO YEAR RESEARCH PLAN	12
Theoretical studies	12
Observational Efforts	13
To be kept in mind	13
A Two-Year Program	13
SUMMARY AND CONCLUSIONS	14
BIBLIOGRAPHY	16
General Works	16
Physics of Astrophysical Jets	17
Galactic Studies	20
Stellar Studies	25
Solar Studies	31

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INTRODUCTION

Jet phenomena are playing an ever-increasing role in modern astrophysics, and seem to represent a fundamental mode of operation of centrally condensed systems in dynamical evolution. We see evidence for matter ejected in thin streams, and in opposite directions along a line passing through a central object, on both stellar and galactic scales. The phenomena is particularly striking because of the high degree of collimation observed and because of the high velocities associated with the ejected matter - in some cases, a respectable fraction of the velocity of light.

The occurrence of processes accelerating matter to relativistic velocities in narrowly collimated beams on such different scales suggests the possibility of further scaling: perhaps even to laboratory size. This might make it possible to construct propulsion systems with *very* high specific impulse. The purpose of the this Phase I study is to determine how this possibility may be fruitfully investigated.

Defining Jets

As it stands, the word "jet" says both too little and too much. Too little because we have not specified exactly what we are going to use the label for; too much because the word implies organized motion along the linear structures so labeled, and this, in all but a few cases, is not directly observed. We propose to deal with these ambiguities as follows:

A morphological definition:

Following Bridle and Perley (74)*, we shall use the word "jet" to refer to structures in both optical and radio maps which are at least four times as long as they are wide and which are aligned with a nearby compact core source.

The problem of flow along the jet structure:

Despite the fact that motion along the jet is unambiguously detected in only a very few sources, assumption of such motion seems very reasonable as a working hypothesis. We shall make this assumption in our investigations, but always with the knowledge that it is only an assumption. Indeed, as we shall argue, obtaining evidence for or against this hypotheses should be one of the goals of the proposed research.

* Numbers in parentheses refer to entries in the bibliography in section X.

Some examples:

A couple of examples may serve to clarify our definition of astrophysical jets. The first is a set of maps of the jet in the radio galaxy NGC 6521, made with a number of different resolutions. It is taken from the review article of Bridle and Perley previously cited, and appears as figure 1.

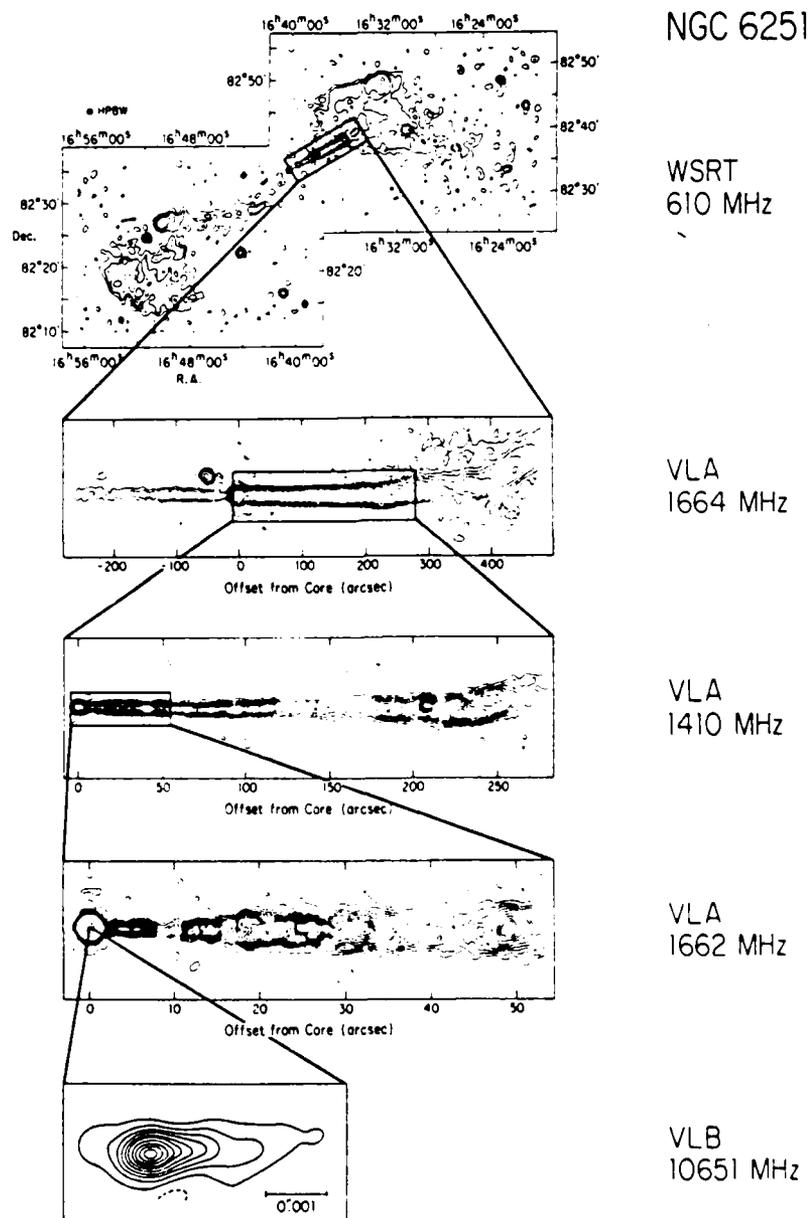


Figure 1. Jet and counterjet of NGC 6521 at several scales, from Bridle and Perley. (74)

These beautiful maps exhibit clearly many of the puzzling aspects of astrophysical jets. We see the double lobed large scale structure implying material flow in two opposite directions. We also see the very asymmetrical intensities of the inner jet structure on the two sides of the central object. This symmetry/asymmetry contradiction will return to trouble us later in this report.

For our second example, we can do no better than to introduce the remarkable object SS433. Discovered in a survey of H-alpha emission stars by Stephenson and Sanduleak (197), it was soon found to exhibit a bizarre and variable optical spectrum. (Margon, et al. (1970)) This spectrum seems best modeled by two jets of hydrogen emitted in opposite directions, at 26% of the velocity of light, from a precessing double system. A high resolution radio map made by Spencer (196), is shown in figure 2, and shows good agreement with the optical model.

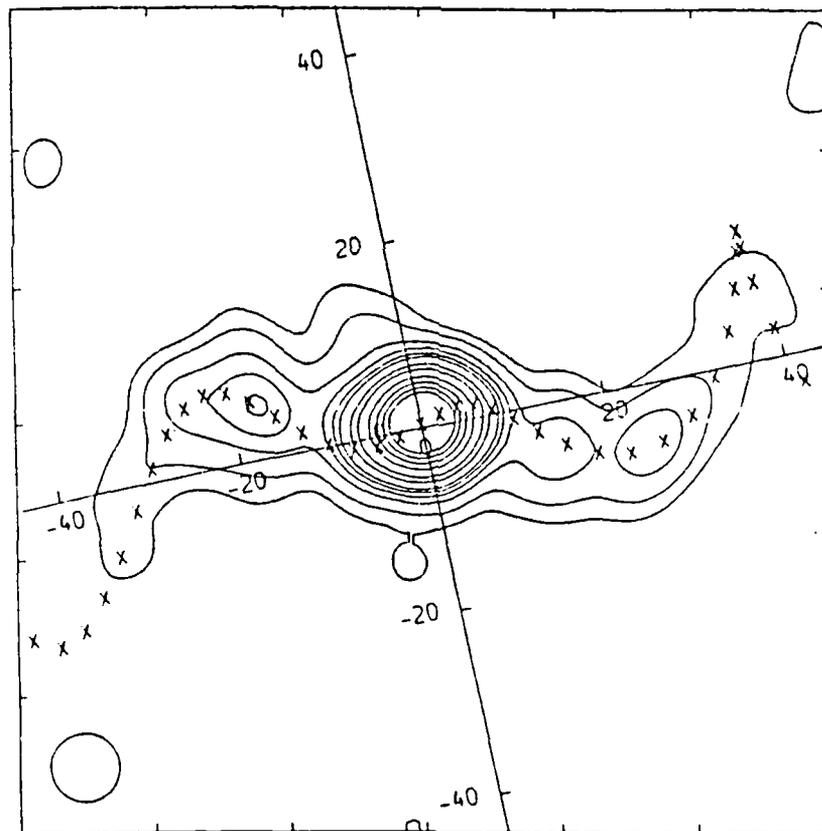


Figure 2. 18 cm map of SS433 with calculated position of ejected material from optical model indicated by x's. Units indicated are in light days at 5 kpc. (from Spencer (196))

These two examples illustrate the vastly different scales on which jets occur. A typical galactic jet may have a length of 100 kpc or more. The jet in SS433 is only of the order of 0.1 pc. Here we see that the ratio of lengths is $\approx 10^6$, while the ratio of masses of the two systems is of the order of 10^{11} . As will be developed in section III of this report, there is evidence for relativistic mass motion in galactic jets as well.

STELLAR AND GALACTIC JETS

To give a flavor of both the similarities and differences among stellar and galactic scale jets, the following table presents some "typical" cases. The column labeled "S" represents the sidedness of the jets.

TABLE OF JET PROPERTIES

OBJECT	CLASS	SUBCLASS	VELOCITY	S	SIZE	REFS
NGC 6521	galaxy	—	?	1	160 kpc	74
3C273	galaxy	superluminal	$> .98c$	1	39 kpc	116
SS433	star	SNR	$.26c$	2	.07 pc	171,196
R Aqu	star	CV	700 km/sec	1	.007 pc	195
HH 28, 29	star	H H object	200 km/sec	2	.23 pc	189

(Velocity and size estimates in this table are to be taken as very approximate.)

If our argument for scaling is to hold up, we must convince ourselves that jet processes on stellar and galactic scales are really related phenomena and not just a morphological coincidence. To this end we briefly review some pertinent observations and models.

Galactic Jets

Since the determination, in the early days of radio astronomy, that many of the most powerful radio sources were extragalactic, the problem of the ultimate energy source for these objects has engaged the astronomical community. The high degree of polarization in many of the sources, together with their non-thermal spectrum, has led to a general consensus that the synchrotron mechanism is responsible for the radio, and, in some cases, some of the optical radiation from these objects. This mechanism, together with determinations of distances by the red-shifts of the central galaxies (presumably the origin of the relativistic electrons involved) leads to energy requirements of the order of 10^{52} ergs for these objects. This corresponds to the total conversion to energy of stellar masses. The only known model for such conversion involves condensed objects: i.e. black holes. Matter falling into such a singularity must radiate its entire rest energy by some

mechanism or other. If matter is in-falling in this fashion, conservation of angular momentum suggests an accretion disk must be formed as an intermediate stage. Such a disk also provides a natural symmetry axis, helping to explain the predominantly double-lobed structure of the extra-galactic radio sources. Thus we may summarize by saying that energetic considerations lead to models involving black holes and accretion disks.

Stellar Jets

Jet phenomena on stellar scales presents an even more diverse picture than do the galactic jets. We may divide the observational material into several categories:

Old Systems

Here we encounter systems moving toward the end-point of stellar evolution. At least one star in such a system will have exhausted its central store of hydrogen and will be undergoing mass loss in one form or another.

Supernova Remnants (SNR) In these cases the mass loss has been really spectacular. The entire outer envelope of the star has been ejected in an explosive event whose luminosity briefly rivals an entire galaxy of stars. Remaining at the center of the expanding shell of gas is a condensed object: a neutron star or a black hole. Only a very few SNR's exhibit jets, but the most spectacular local jet we know of, SS433, has been identified with the central object of W50, a supernova remnant some 5 kpc distant from the earth.

This complicated system is very well modeled as a double sided jet emerging from a binary system with an accretion disk. A useful review of our current understanding has been given recently by Margon. (171)

One sided jets have also been identified in the Crab nebula (see Velusamy (200) and Woltjer and Veron-Cetty (203)) and possibly in two southern supernova remnants (Kesteven, et al. (163)). These objects are considerably weaker, and hence much more difficult to study in detail, but suggest that SS433 is not a totally isolated case.

Cataclysmic Variables (CV) Cataclysmic variables are considerably less spectacular than supernovae, but nevertheless exhibit sudden large changes in luminosity. Novae fall into this class of stellar system. All these objects are in binary systems, and are frequently best modeled with accretion disks. Here the star losing mass is the less evolved of the pair, and some of the mass lost forms an accretion disk around the more evolved member: a compact object, usually a white dwarf. Jet phenomena has been observed in at least three symbiotic systems (systems that share a common atmosphere): AG Peg (Hjellming (160), R Aqr (Sopka, et al. (195)) and CH Cyg (Taylor, et al. (198)).

Young Systems

We turn here to star systems just now forming — objects evolving onto the main sequence. These systems are difficult to study at optical wavelengths, since they are still enveloped in the dense gas and dust from which they are condensing. Associated with a class of these stars, the T Tauri stars, are phenomena of interest to this study: the Herbig-Haro objects. These are luminous features seemingly ejected from a central region. They may frequently be associated in pairs lying on a line through a central condensation, with oppositely directed velocities of up to a few hundred kilometers per second. Since the formation of planetary systems must involve an accretion disk like stage, it is tempting to associate these features with jet-like ejections from that disk. A recent review of these systems has been given by Schwartz. (189)

Thus we see that in both the galactic and stellar cases we have evidence for a common geometry: an accretion disk surrounding a central condensed object. This suggests that jet formation and accretion disks may be related phenomena, and indeed most of the models suggested for jet formation have relied on an accretion disk to provide either the immediate energy source, the collimation mechanism, or both.

The models are otherwise quite diverse, and before turning to a closer examination of the current leading contenders, it will be useful to examine another aspect of the jet phenomena: the time variability scale.

TIME SCALES OF JET PHENOMENA

A study of the time scales of variability of astronomical phenomena is interesting because it directly gives limits for the linear size of the source of the varying radiation. Clearly, if we are observing radiation coming from a region of size r , any changes with time scale less than r/c , where c is the velocity of light, will be averaged out. One of the real surprises of radio astronomy was the discovery of short time scale variation (months, weeks, and even days) of sources at cosmological distances, identified with very distant galaxies. Even more puzzling was evidence from very long baseline interferometry (VLBI) of so-called “super-luminal” expansion: apparent expansions of distant radio source components at multiples of the velocity of light. As above, we may divide the available observations into several categories.

Galactic

We consider first “normal” variations of extragalactic sources; i.e. those which do not overtly exhibit so-called superluminal motions. Since the pioneering work of Dent and collaborators at the University of Wisconsin in 1965 (84), many sources have been monitored for flux and/or polarization changes. A recent review

of this material has been given by Pearson and Zensus (115). In general, such variations as are observed were taken to indicate that *very* condensed objects were the source of the radiation. Since the development of the mass motion models required to explain the superluminals, however, analogous arguments have been used to relax the scale size requirements, at the cost of requiring rather preferential orientation of jet motion toward the observer, in order to "blue-shift" longer term variations to the rapid changes observed.

The so-called "superluminal" sources were first identified by Gubbay and collaborators (90) when comparing VLBI maps of 3C279. Although not perfectly unambiguous, their results could be interpreted as revealing the ejection of clouds of relativistic electrons with transverse velocities of some 3 times the speed of light. Later, more refined, observations confirmed the apparent superluminal motions (based, of course, on cosmological distances for the sources, determined by red-shift measurements of the central galaxies), and many other objects were also observed to exhibit this behavior.

Although many problems remain, there does seem to be some consensus on a bulk relativistic motion model to explain these observations. Material with near light velocities, ejected almost directly toward the observer, can appear to have transverse velocities of multiples of light speed without violating known physical laws. As mentioned above, such models are also useful in understanding very short time scale variations of objects of galactic dimensions.

Stellar Systems

In general, time variability of stellar systems have presented no such seemingly impossible puzzles. Since stars are only light minutes in size at most, they are "allowed" to vary rapidly. Here again, we divide out material into various classes.

Old Systems

Only four Supernovae remnants have been identified as exhibiting jet structures. Of these, only two, SS433 and the Crab nebula, have long enough histories to make time scale studies possible. Indeed, the observed proper motion of material ejected from SS433 has permitted, when combined with the well determined optical velocities, an accurate distance determination. (171) The two southern SNR's (163) with possible jets have no variability data known to the author.

Evidence for jet-like structures in cataclysmic variables is not extensive. Four or five symbiotic systems seem to exhibit jets, but no variability studies of these structures are found in the literature. This would seem a fruitful field for future research.

Young Systems

Rather extensive studies of variations of Herbig-Haro objects exist in the literature. (See the review by Schwartz, and references therein. (189) Due to the obscuration at visual wavelengths of these regions, there is considerable ambiguity in the interpretation of these results, since changes in the obscuring material cannot be readily distinguished from changes in intrinsic luminosity or position.

SOME CURRENT JET ACCELERATION MODELS

A number of approaches have been used in attempting to understand the acceleration of matter in astrophysical jets. The crudest possible models involve simple mechanical collimation of expanding gas by an accretion disk. More sophisticated calculations which consider stellar winds interacting with various inhomogeneous condensations are well represented in the literature. (See, for example, Boss (16), Fukue and Yamamoto (27), Melia (43), Sakashita and Hanami (47), and Tenorio-Tagle and Rozyczka (53), among many others.)

A less conventional view has been taken by Fryxell et al. (26). They consider the hydrodynamic consequences of the supersonic motion of a star through the interstellar medium. Under some circumstances, they predict that single-sided, and in others, double-sided jets will form. Their numerical models do not consider magnetic field effects, and, of course, the jets formed are non-relativistic.

Kaburaki and Itoh (36) study an analytic model of ionized jets driven by thermal forces but collimated magnetically. They propose the application of this model to the T Tauri class of stars, since the velocities so produced are in the range observed in the Herbig-Haro objects.

Such models are moderately convincing when discussing the processes which occur in the formation of stellar systems, but fail when relativistic jets are to be explained.

More general magnetohydrodynamic calculations are, of course, much more complicated, but open the possibility of acceleration of material to relativistic velocities, as well as promising unified models of jet formation on all scales. The numerical studies of Shibata and Uchida (48, 49, and 57) seem particularly promising in this regard. Using a 2.5 dimensional code, (cylindrical symmetry but non vanishing velocity and magnetic field in the rotational direction) they not only successfully modeled magnetic acceleration of jet plasma, but predict a hollow jet structure, with helical magnetic field, much like that recently observed in high resolution studies of the jet in Virgo A (93). Their calculations are, as yet, only for the non-relativistic case, but extension to the relativistic case may be expected in the near future.

The only calculations known to the writer to deal with the production of relativistic jets are those of Lovelace and collaborators (39, 40, and 51). While these workers do not specifically treat the particle acceleration mechanisms, they show, in several analytic models, that relativistic flow in magnetically self-collimated jets is a solution to the relativistic magnetohydrodynamic equations with boundary conditions appropriate to a plasma accretion disk in the vicinity of a condensed central object. While the published material is primarily restricted to several special cases, (in particular, such that the fraction of the jet energy carried by matter is very small), it is anticipated that more general cases will be forthcoming in the fairly near future.

In essence, in the treatments of Shibata and Uchida, and of Lovelace, et al., discussed above, a preexisting poloidal magnetic field is twisted and amplified by the plasma accretion disk, until various instabilities produce an axial flow of plasma, radiation, and now helical magnetic field. Angular momentum is also removed, permitting matter to spiral in to the central condensation. These models seem sufficiently realistic to offer hope of a unified set of models for both stellar systems in formation and the more spectacular processes occurring in the vicinity of the collapsed objects thought to represent the end point of stellar evolution.

COMPARISON WITH OBSERVATIONS

In all of the phenomena discussed above, we have been looking at systems which convert gravitational energy into radiation and kinetic energy of ejected plasma. All of the systems discussed have rotational symmetry (to zeroth order), and most of the jet models permit contraction by removing angular momentum from the system.

While the numerical studies can be very informative, ideally we would like to extract possibly observable invariants from the analytical models. A couple of caveats are in order. First of all, *no* analytical model yet covers the transition to relativistic motion. Indeed, the only analytical model that touches the relativistic case, that of Lovelace, et al., treats the particle velocity as a constant of the motion. Secondly, it is far from clear that one model will fit all cases. It is perfectly conceivable that several different mechanisms operate to produce jet-like structures. Indeed, Canto, et al. (139), have questioned whether many of the stellar jets identified are not just projection effects.

Nevertheless, the extraction of invariant observable relations from the several models available could serve very useful purposes. In the first place, they might serve as falsifiable predictions of the models involved. Secondly, they might suggest possible approaches to laboratory scale testing, if cast in the proper form. Thirdly, since measured velocities for jets exist in only a few cases, general relationships derived from both relativistic and non-relativistic models might serve as a sort of "jet speedometer".

Unfortunately, no model currently known to the author readily lends itself to this sort of approach. In some measure, this is due to the paucity of real data available. Velocity, magnetic field strength, density and composition of the jet material, are in almost all cases, simply unavailable. The state of modeling these phenomena at present also presents certain problems.

QUESTIONS AND PUZZLES

In this section, we shall address a number of questions which have been more or less "swept under the rug" in the foregoing sections. Our treatment of astrophysical jets and the models which have been proposed to explain them has adopted the "standard assumptions" common to discussions in this field, and the relativistic beaming model has certain problems as well. Honesty and completeness demand that we now at least mention these assumptions and problems, since it is possible that they point the way to challenges of great consequence to our understanding of the universe.

A Note on the Cosmological Distance Assumption

It seems prudent to begin with our assumption that the red-shifts of distant galaxies really do measure their distances. Although seemingly well established, it is still called into question occasionally, most recently perhaps, by Narlikar (112). Quite a thorough compilation of material on this whole question was published not too long ago by Field (6). Obviously, if the quasars and superluminal radio sources are quite nearby, no relativistic beaming models are necessary.

It is the authors view that the vast weight of the evidence is clearly in favor of the standard interpretation of the red-shift as a distance indicator. While the actual values of the Hubble constant and the acceleration parameter are still quite controversial, it seems most certain that the Hubble constant, at least, is known to within a factor of two or so. And that uncertainty is not enough to remove the problems which have been solved with the relativistic beaming hypothesis.

How do we know it's a push and not a pull?

This is the question asked by an engineer friend of mine when I was telling him all about astrophysical jets a while ago. At first I tried to be polite about his stupid question, but, on consideration, it became clear that it was not so stupid after all. Science fiction has used "tractor beams" for years as useful magic, so it ill behooves us to ignore the possibility that we are observing such a thing in the admittedly rather mysterious phenomena of astrophysical jets.

So, how *do* we know that "it's a push and not a pull"? Basically, I think the cleanest evidence is that (in general) the jets expand as they leave the central region. All directed phenomena that we know of have the property of diffraction.

Even solid objects, (e.g. bricks) will develop a "beam spread" due to small deviations of the initial conditions, when we consider a collection, or stream of them projected out in a single direction. Fundamentally, this would seem to be related to the second law of thermodynamics and the direction of time. Therefore we can tell the direction of a beam by looking for expansion.

Problems with the Statistics of Jet Sidedness

The relativistic beaming model for the superluminal sources suffers from the requirement that the jets we see must be beamed selectively toward us. This implies that there should be an even larger number of such jets which are *not* beamed toward us. Where are these objects? Furthermore, if the predominant single sidedness of this phenomena is caused by so-called "doppler favcritism", there are additional problems. It can be shown (see Barthel (70) and references therein) that for sources whose jets lie within 15° of the plane of the sky, then even for jets moving at the velocity of light, the jet/counterjet ratio cannot exceed 5. For random orientations, the probability of a system lying within 15° of the sky is 26%. This simply does not square with the statistics of the observed sources.

QUESTIONS FOR INVESTIGATION

As we have reviewed the astrophysical jet situation in this report so far, certain questions have been suggested or pointed out. In this section, we shall lay out concretely a number of problems that seem ripe for investigation.

What sort of systems are ejecting the H-H sources?

If, in fact, all jet phenomena are connected with accretion disks (or proto-planetary disks), then we should search for them in all locations where we find material being ejected in jet-like fashion. The T Tauri systems associated with Herbig-Haro objects are a very natural place to look. How might we detect them? Perhaps infra-red observations are the most likely possibility, although if magnetic forces and processes are involved, VLBI mapping would also seem profitable.

Is there a disk in the crab?

It is well known that a pulsar exists in Tau A, (The Crab Nebula). Is there also an accretion disk? This may turn out to be a theoretical modeling problem, since the brightness and complexity of the dense ionized material in the Crab makes it difficult to distinguish many details.

Does a jet exist in SN1987a ?

Shortly after the discovery of the new supernova in the Large Magellanic Cloud last year, two groups discovered a second bright feature a few arc seconds away from it, which later seems to have disappeared. (188) Its distance and brightness made a light-echo model unlikely. While there is always the possibility of "non-reproducible results", i.e. some sort of observational error, it is tantalizing to speculate on the possibility of the existence of another relatively nearby jet in a supernova.

Possible Secular Changes in the Vir A Jet

The beautiful fine structure shown recently in the jet in Vir A (93) is of such small scale that changes may possibly be observed in just a few years. If this were the case, we would have another actual velocity measurement in a jet, and this time, in a galactic scale one.

The Question of Material Motion Along the Jet

If we are to gain a good understanding of the jet phenomena it is very important to gain added information on the material properties of the jets themselves. We desperately need solid values for density, velocity, and magnetic field strength. At present we have reliable velocity data for a handful of objects. This data will not be easy to obtain, but any progress along these lines would well repay the effort necessary.

A TWO YEAR RESEARCH PLAN

Given the many unknowns and uncertainties of the astrophysical jet phenomenon, the problem is not what to look at, but what to select as offering the best possibility of increasing our understanding of these processes. Possible efforts fall naturally into two broad categories.

Theoretical studies

Rapid progress is being made by at least two groups at the moment: that of Lovelace and collaborators at Cornell, and by the Japanese group represented by Shibata and Uchida. In the view of the writer, the work of these two groups complement each other very nicely. The Japanese group, coming from a background of Solar Physics tend to emphasize detailed study of the plasma interactions and numerical studies, while Lovelace, et al. try to put the global picture in a good analytical framework. It seems very important to follow developments in these two groups closely, in order to extract from their theoretical efforts invariant expressions that will lend themselves to observational and experimental testing.

In addition, considerable study should go into the possible application of results and observations in the field of Solar Physics and laboratory plasma physics to the astrophysical jet phenomena. Effort in this direction is rare, since communication between Solar and other astronomers is not very good. Nevertheless, just for this reason, the effort should be quite fruitful.

Observational Efforts

In the meantime, there are several crucial areas that seem ripe for new observations. The detection of disk-like features and any associated magnetic fields or relativistic particles associated with Herbig-Haro objects is a prime example. Such detections would offer support for a single unified jet mechanism, while the demonstration that no particular unifying geometry was present would suggest that there are at least two distinct mechanisms in nature producing jet-like phenomena.

Similarly, evidence for relativistic particles associated with the jets detected in the symbiotic objects would strengthen the unified model case. Independent evidence for accretion disks in the Crab nebula and SS433 would also nicely complement these studies.

In the case of the extra-galactic jets, the time development of the fine structure of the jet in Virgo A will be extremely important. A map similar to that presented by Hardee, et al. (93), made in a year or so, would be most enlightening. Obviously, it is also most important to follow the evolution of the recent supernova in the Large Magellanic Cloud (SN1987a). The suggestion of a relativistic jet provided by the mysterious "companion" observed briefly (188), certainly needs to be followed up with deep radio observations.

To be kept in mind

As mentioned, all of the (non-solar) jet phenomena are in very special systems: vast, rotating disks falling lower into the gravitational well of a centrally condensed object. If the jet phenomenon is to be harnessed for propulsion purposes, an energy source other than the gravitational one must be found. This seems *the* crucial point for eventual practical application of these phenomena. The contribution of solar studies and laboratory plasma physics is absolutely vital here.

A Two-Year Program

In attempting to lay out a two year research program, several factors must be kept in mind. First, due to lead time requirements for obtaining telescope time, observing proposals need to be prepared early in the effort. Secondly, in order to make timely use of recent theoretical results, close contact with theoretical research groups is vital. Thirdly, since the eventual goal is practical application

of the physics involved, an interdisciplinary point of view is required, and efforts to combine points of view of solar physics, laboratory plasma physics, and astrophysics must be emphasized. All of this represents a major effort, and in two years, we may realistically only expect to make a strong beginning. Bearing this in mind, then, a responsible approach might be as follows:

During the first two to three months, efforts will emphasize the preparation of proposals chosen from the following:

- 1) Observing proposals for the VLA and US-VLBI network to make high-resolution searches for evidence for accretion disk-like features and the presence of relativistic particles in T-Tauri and symbiotic jet systems.
- 2) Searches of available infra-red and X-Ray data bases for correlative data on these objects.
- 3) Investigation of the possibility of obtaining high-resolution radio studies of the possible jet in SN1987a

For the following four to six months, emphasis will be on obtaining invariant combinations of observables from the latest results of the Cornell group (Lovelace, et al.) and the Japanese group (Shibata and Uchida), followed by preparation of observing proposals, as seems useful, on the basis of the results obtained.

At this point, telescope time grants from the first proposals should be coming on line, and effort will be directed toward making the observations and reduction of the resulting data.

Following writeup and publication of this data, the second round of observing proposals should be bearing the fruit of telescope time allocation, and the process will be iterated.

Interspersed with these efforts will be attempts to obtain and apply solar physics and laboratory plasma physics results to these problems.

A Phase II proposal, to be submitted shortly, will offer a more detailed research plan.

SUMMARY AND CONCLUSIONS

We have seen, then, that astrophysical jets may indeed possess a common geometry: an accretion disk, or protoplanetary disk of plasma which entrains and modifies the ambient magnetic field. This produces an axis of symmetry out which material can flow, collimated, and perhaps accelerated by the modified field. In spite of the rapid progress in this field in recent years, many questions remain. Are

all jets accelerated magnetically, or is there a class of "thermal jets" as well? Is the difference between relativistic and non-relativistic jets simply due to differences in the density of the central object, or do other environmental conditions also play a role? And what of the intimate details of the magnetic acceleration process? Is it necessary to have a central gravitational well to produce these powerful and well collimated jets, or might we conceivably build laboratory devices operating on the same principles? Here, clearly, attention must be paid to processes occurring on the Sun. We know that relativistic particles are produced by solar magnetic disturbances. Are there common mechanisms?

We are confronted by two vastly different, and very difficult problems. We can observe extremely high-energy processes in the universe, but at great distances, and with many ambiguities. In the laboratory we have control, but the processes are very complicated and the energies are, perforce, low. Clearly, progress may be expected to occur most rapidly if these problems can be attacked from both ends. Our aim should be to attempt to reproduce effects observed in the universe in the laboratory, and at the same time, to utilize principles learned in the laboratory to advance our understanding of astrophysical processes.

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