CYGNUS A:
SOME TOPICS FROM THE WORKSHOP

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1. Introduction

The international workshop on Cygnus A was held in Green Bank WV, USA and was attended by 45 participants who reported on radio, infrared, optical, UV, X-ray, and theoretical results. Rather than attempt to cover all of the papers presented at the workshop, we have selected 8 topics. We apologize to those whose work is not mentioned here. Because of the limitations of length, we have foregone the luxury of figures and we refer to articles in the Cygnus A book (to be published early in 1996 by Cambridge University Press) by first author only. All references to page and figure numbers refer to the Cygnus A book.

2. Central Region

2.1. THE HIDDEN QUASAR HYPOTHESIS

The currently popular model for 'unification' is based on the concept that quasars and radio galaxies are intrinsically the same; only the viewing angle produces the different characteristics by which we assign them to different classes. An integral part of this model is the presence of an obscuring torus which blocks optical and UV emissions from the nucleus and broad line region when the jet emission axis lies more or less in the plane of the sky rather than pointing towards us. Since Cygnus A is a high luminosity radio source, many observers predicted that it would be an ideal test of the unification model and many attempts have been made to look for the observable consequences. The results have been mixed.

With long slit spectra, Tadhunter and Cabrera-Guerra searched for evidence of an EMISSION CONE OF IONIZING RADIATION, expected to

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escape along the axis of the torus (i.e. coincident with the radio jet). Tadhunter plots the variation in the [OI]/[OIII] ratio for an off nucleus slit perpendicular to the radio jet. He finds a 'horseshoe' shaped curve (fig4, p36), "strong evidence for an anisotropic ionizing radiation field". Cabrera-Guerra found a similar effect for [OII]/[OIII] (fig5, p30), but Tadhunter remarks that when calculating the absolute number of ionizing photons, there is less ionizing radiation from the nucleus than most quasars and there is no evidence for horseshoe patterns for [NII]/Hβ or [SII]/Hβ.

The FEATURELESS BLUE CONTINUUM has been studied by many workers to see if it might be evidence for scattered light from the nucleus, either by dust or by free electrons. Other possibilities for its origin are star formation regions or free-free emission. Antonucci finds no Balmer edge (expected from A stars) so he concludes it is not predominantly normal star light. The polarization is found to be 2.5% rather than the expected 30% for scattered light (Stockton, Tadhunter). Furthermore, the narrow lines are not polarized. Therefore, scattered light is not the dominant component, and free-free emission is also a minor contributor (Stockton, p3). The general consensus was that star formation dominated, an explanation which was bolstered by an HST photo which shows extreme knottiness.

Is there any evidence for a BROAD LINE REGION? So far, Antonucci's MgII line are the only data which support the notion of reflected light from a BLR. Stockton failed to find a broad component in some infrared lines (<800km/s), Ward found no broad Paα, and no scattered component of emission lines was found (e.g. Hβ or in polarized light; Stockton, Jackson).

There were doubts expressed about the POWER of the hidden quasar. It was pointed out by several participants that the power from the core in radio, infrared, and X-rays is characteristic of a rather modest quasar; Cygnus A can be classified as a high luminosity source only with respect to its radio lobes. If there is a quasar-like nucleus, it is of medium or low power.

If there is an obscuring torus, the dust should have associated CO and other molecular lines in absorption. Barvainis searched for CO in absorption but failed; $\tau < 0.6$; $N < 10^{16} cm^{-2}$. There is also no ammonia, which is a more complex molecule than CO, and hence may not be as amenable to some of the explanations - see below - for the lack of CO; $\tau < 0.1$. Maloney suggested methods to save the molecular torus via radiative excitation. Another suggestion for the paucity of CO could be that the gas is mainly atomic; if NH < E23.5cm^{-2}, Maloney argues that the gas will be atomic. Blanco detects HI (fig1, p71), but no formaldehyde nor OH. From various arguments, Blanco deduces that the most likely location of the HI is 4pc < r < 1 kpc, thus it is still an open question if the observed HI can be associated with a (small) obscuring torus. VLBI observations are planned.

Another necessary consequence of an obscuring torus is ABSORPTION of SOFT X-RAYS. Arnaud reported on GINGA and ASCA data, providing evidence for a hard x-ray component with a power law. These conclusions depend on spectral fitting; both detectors have poor spatial resolution although the characteristic 'X' shaped Point Response Function of ASCA is visible in the 6-9 keV image, showing that the hard source dominates over that of the extended gas at these energies; the inferred diameter is $< 1'$. The visual extinction estimates cover a wide range: Av = 40 from the Lx vs. L(Hα) relation together with Paα/Hα=0.1 (Ward); Av = 120$\pm$25, from a comparison of 3.5 micron and hard X-ray intensities (Ward); and Av > 150 (log N = 3.7E23) from x-ray spectral fitting (Arnaud). A somewhat perplexing complication is that with the ROSAT HRI (resolution 5") we have detected a discrete source coincident with the radio nucleus to 0.5". For the large extinctions found, essentially no photons in the ROSAT band should be visible. One escape from this problem was mentioned: the observed X-rays could be scattered core emission, thereby following a path that evades passage though the torus.

Generally, the evidence for a hidden quasar remains weak. What was once considered as the great hope and test of the unification scheme has failed to deliver conclusive proof. While it is true that various ways have been found to explain the failures, it seems to us that viewing angle is not the sole difference between radio galaxies and quasars. The unification scheme that appears more promising is that which depends on the fundamental source of the energy release around black holes:

Predominantly gravitational/accretion => radio quiet Q/AGN
Predominantly rotational energy => radio galaxy
Both sources are comparable => radio quasar

2.2. DO THE JETS CAUSE OBSERVABLE EFFECTS IN THE ISM?

There was considerable speculation about the cause of the DARK CHANNEL in the NW emission region about 1.3" from the nucleus which coincides with the inner radio jet at a point where the VLA jet intensity reaches its first minimum (Cabrera-Guerra, fig2, p27). Although several of the optical experts opined that its sharp edges suggested dust obscuration, no one offered a plausible explanation for dust enshrouding this segment of the jet and it was later pointed out that there is no evidence for reddening in this area. If the emitting region has been evacuated by the jet, then the region must be 2 dimensional, a possibility that most considered to be unlikely.

Is there evidence in the Extended Emission Line Region for SHOCKS from the RADIO JET? Stockton finds higher excitation (e.g. [OIII]) mainly aligned with the jet; away from the jet, to north and south, the excita-

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tion is lower([NII]). From line diagnostics, Clark points out that Cygnus A emission is similar to that found from radio knots close to the nucleus in other powerful radio galaxies rather than that from hotspots and lobes. The former type is characterized by higher ionization and smaller line widths, interpreted to favor photo-ionization over the collisional excitation which would have been evidence for shocks. At IAU175, Bicknell remarked that strong shocks can produce ionizing radiation which thus becomes the intermediary for line excitation which appears to be photo-ionized even though the primary energy is supplied by shocks.

There is also evidence for HIGH VELOCITY GAS. Stockton finds components of [OIII] at 1400 and 1700 km/s blue shifted near the western jet and at 700 km/s redshifted on the other side of the nucleus. He notes however, that the western location is 700 pc from the radio jet. From narrow slit spectra Cabrera-Guerra show that line widths of [NII] increase near the western side of the jet (fig4, p29).

We find these data to be convincing evidence of jet/ISM interaction, although the precise details are far from clear.

3. The Jets

3.1. THEORETICAL ASPECTS

Both Lovelace and Roland develop models which accommodate gamma ray production (as in blazars). Lovelace proposes a Poynting flux jet with eventual pair production and IC radiation from pairs scattering the UV from the nucleus. Roland also uses pairs for gamma ray production, which occurs about 2 light weeks out from nucleus. He suggests a two fluid jet consisting of relativistic e^+/e^- to produce the VLBI structures and gamma rays, and a mildly relativistic p^+/e^- component for the large scale jet and to provide the energy transport to the hotspots and lobes. Hardee's simulations show that a light jet breaks up. However, with a jet density = 4x the external density, the jet is able to propagate for long distances.

For Roland's two fluid jet, the total internal pressure = (thermal+rel protons+rel electrons+B). For the jet to propagate, this must be > external pressure. If the jet is weak, and $\rho v^2 <$ the external pressure, the jet never propagates to large distances, forming instead a bright, short jet like M87. Thus Roland suggests that the difference between FRI and FRII depends on the ram pressure vs. the external pressure; i.e. both the strength of the jet and the ICM (or ISM) pressure are important.

3.2. THE MORPHOLOGY OF THE LARGE SCALE JET

On the kpc scale, the observed morphology of the western jet as it leaves the galaxy and enters the lobe consists of regularly spaced brightenings with a wavelength of 7″, about 10 times the jet radius (Carilli, fig5, p82). These features are inclined about 7°, and could, like M87 be a sort of braiding. Hardee presented the results of simulations of emission and dynamical properties of magnetized jets (a dynamically important magnetic field is included). For a Mach 8 jet with density = 4x the external density, he finds instabilities (pinch, helical, kinks, fluting) which propagate as wave modes down the jet. Both surface waves and body waves are present, and this combination is able to produce oblique filaments (caused by an enhanced B field) from phase differences of helical and elliptical twists (fig1, p115).

Clarke suggests that the physical jet could be much wider than the observed radio jet. This helps the theoretical problem of jet stability. The thin radio jet would then be one edge of the physical jet, and the bifurcated section would just be a piece where both edges were illuminated.

4. The Hotspots

The chief uncertainties for the hotspots are the X-RAY EMISSION PROCESS, the ENERGY DENSITY and MAGNETIC FIELD STRENGTH. The jet composition (i.e. the presence or absence of protons) is part of the answer to these questions. Are the x-rays really synchrotron-self Compton (SSC) photons or might they arise from synchrotron emission (i.e. from the so-called 'proton induced cascade', PIC, process)? What are the energy density and pressure? Does equipartition hold?

The observed spectrum from the radio to optical was reviewed by Roeser (fig2, p125). Hotspot D is empty, A appears to be an M star, and B has another star in the foreground (fig1, p122). Fitting the observed spectra with the usual Fermi acceleration models, Roeser finds, for hotspot A, a break frequency of 5.5 GHz, a cutoff frequency of 9E12 Hz, and a B field of 340 μG. The corresponding values for hotspot D are 10.8 GHz, 8E12 Hz and 400 μG.

Harris reviewed the situation for SSA and PIC as the genesis of the observed X-rays (ROSAT HRI results). For SSA emission, magnetic field strengths are 160 μG (hotspot A) and 245 μG (D). These field strengths are strict lower limits, and they also agree with equipartition fields for the case of little or no energy contribution from relativistic protons. If, however, protons dominate the particle energy density, then either the hotspots are far from equipartition (with a weak field and SSC X-rays) or they would have a field $\geq$ 500 μG and SSC would be a minor contributor to the observed X-rays. In this case, some other process such as the PIC would have to supply the extremely energetic electrons required to produce synchrotron X-rays. Note that the weak field/no proton scenario requires the absence of protons in the hotspot and therefore the jet itself could not contain protons.

An interesting ramification of the PIC process is the generation of ultra high energy protons (to initiate the cascade, protons with Lorentz energy factors > 3E11 are required). Biermann discussed the implications of this for the highest energy cosmic rays observed at the Earth. When the cosmic ray energy is above 3E18eV, they cannot be contained by our galaxy. At this energy, the main constituent changes from medium heavy nuclei to protons. Arrival direction suggests the super galactic plane (fig3, p145).

5. Equipartition in the Radio Lobes

Equipartition between magnetic field strength and energy in relativistic particles has been questioned in three ways. In each case, the suggestion is that the particle energy density dominates over the magnetic field energy density. From numerical simulations with 3D hydro code (plus a trace magnetic field), Clarke is able to generate synchrotron emitting filaments in the lobes (aka 'cocoons'). They appear to be features with enhanced field strength, formed by stretching the B field; therefore Clarke reasons that u(B) < u(gas) + u(particles) and, if filaments are seen (as is the case for Cygnus A), it is probable that the B field is significantly below equipartition (NB: in this case 'equipartition' refers to that between the B field and the relativistic particles + the thermal gas, if the latter is present).

Carilli claims that pressure balance with the external medium requires more than the equipartition field. Furthermore, he calculates that the minimum pressure in the lobes is 7 times less than P(jet). Thus increasing P(lobes) by relaxing equipartition will: confine the jet, balance the external thermal pressure which is known from X-ray data, and allow the jet density > lobe density, providing stability for the jet.

Alexander presents arguments based on ram pressure, advance speed, and aging. Aging arguments give the velocity of separation between the hotspots and lobe material: v = 0.04c to 0.06c; whereas if ρv^2 = P(hs) - P(ext), and the dentist drill model is assumed, (i.e. the average advance speed is reduced by area hotspot/area lobe), then v(hs)=0.005c. Therefore, the B field in the lobe needs to be below B(equip) to change the aging results. To achieve agreement with the advance speed of the hotspots, P(lobe) > 10 P(min).

While each of these approaches has merit, for the most part, they are model dependent (e.g. if the hotspot internal pressure is much higher than minimum, the advance speed goes up, and the third argument is negated).

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6. The Cluster Gas

6.1. THE EFFECTS OF THE LOBES AND THE BOW SHOCK

Clarke has studied various X-ray features evident on the ROSAT HRI image (fig6, p207) with numerical simulations using a 3D hydro code. For a Mach 6 jet with a density = 0.02 x (central density of a King distribution), Clarke was able to reproduce the relative depression in the observed X-ray brightness from the evacuated inner part of the radio lobes. In addition, the higher brightness twin X-ray features most obvious on the eastern side of the source were reproduced in the simulation by thicker parts of the sheath between the bow shock and the radio lobe (fig3, p204). The only X-ray feature not yet understood is the asymmetry between the eastern and western sides. Although the depressions appear on both sides, the twin enhancements of the sheath are almost absent on the western side.

6.2. HOW ROBUST IS THE COOLING FLOW PARADIGM?

The large scale morphology of the X-ray distribution was reviewed by Reynolds from ROSAT PSPC data. Cygnus A lies close to the center of a high brightness, quasi spherical distribution which, in turn, lies at one end of an elliptical region of relatively low surface brightness. The spherical distribution has a diameter of order 150 kpc whereas the long axis of the ellipse is greater than a Mpc. From spectral fits of the x-ray data, the temperature varies from 3 keV (inner part) to 7 keV (outer part). The latter value is in agreement with the GINGA value (fig3, p196). Arnaud reported on the ASCA results: 9 keV for the low brightness gas and 4 keV for the high brightness region. From a deprojection of the ROSAT data, Reynolds finds a central density of $0.03cm^{-3}$, a cooling radius of 180 kpc (H=50), and a mass deposition rate at the center of 250 $M_{\odot}$/yr.

There is no question that there is cooler gas in the center and that the cooling time is shorter than the age of the universe. However, in our view, the 'flow' part of the picture remains to be demonstrated. If there is a flow, where does the 250 $M_{\odot}$/yr go? It would also be useful to see a careful energy budget for the radio source. The main problem with this is that we do not know the actual power of the jet, so we do not know how much energy gets dumped into heating the ICM (by the jet, hotspots, lobes, and bow shock).

7. Conclusions

- HIDDEN QUASAR: Based on the evidence presented at the workshop, there might be a weak quasar-like nucleus but many of the predicted effects are not seen.

- EFFECTS of the JETS on the ISM: Probably present, although these effects may be more pronounced in other sources.

- WHAT ARE JETS MADE OF? Not yet determined.

- CAN WE EXPLAIN the JET MORPHOLOGY? Simulations are very promising with various instabilities reproducing regular spacing, etc

- HOTSPOT EQUIPARTITION and ENERGY DENSITIES: If we could have faith in the accuracy of ram pressure estimates, we could get the total pressure inside, and with that, could probably untangle the components.

- ARE the LOBES in EQUIPARTITION? Maybe not. Several lines of argument were presented that the B field is weaker than other components.

- DO WE UNDERSTAND the main X-RAY FEATURES? Yes (via simulations), but some asymmetries remain unexplained.

- Do 'COOLING FLOWS' REALLY FLOW? Is Cygnus A one of the most powerful heat engines in the universe?

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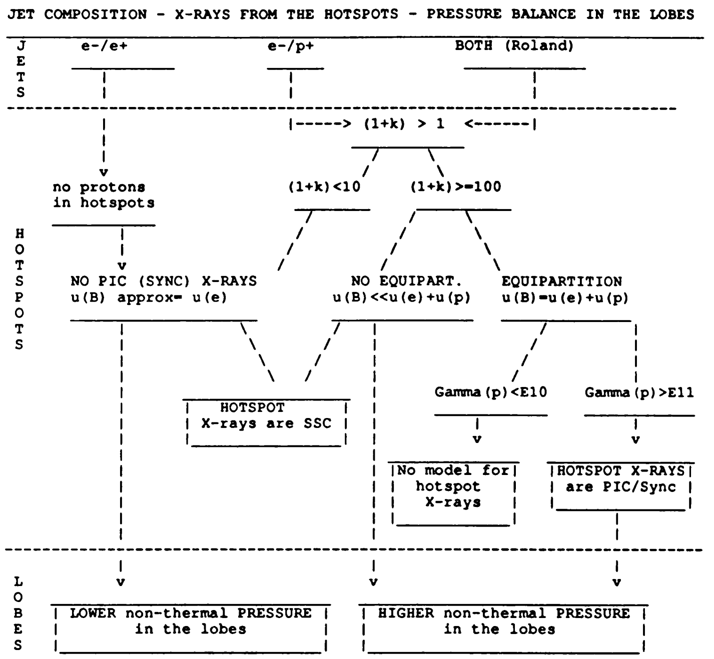
The following diagram shows how some of the questions reviewed above are inter-related.



ASSUMPTIONS:
a) No significant acceleration in the lobes
b) No significant entrainment of ambient gas; i.e. the jets, hotspots, and lobes are 3 phases of the same fluid.

NOTES:
a) k is the ratio of energy in relativistic protons to that in electrons.
b) u is the energy density
c) gamma is the Lorentz energy factor; gamma(p) is the maximum energy for the power law distribution of relativistic protons.