9. SUMMARY

RADIATION HYDRODYNAMICS: CONFERENCE THEMES AND UNSOLVED PROBLEMS

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1 Introduction

This paper will be a short review of the topics covered at this conference on "Radiation Hydrodynamics in Stars and Compact Objects." Rather than attempt to cover all the talks and posters, I will describe what I saw as the main themes and then summarize selected topics that provided unsolved questions. Finally, I will try to decide whether we strayed too far from the original purpose of the meeting. Or, put as a question: Does Radiation Hydrodynamics play a major role in solving a wide range of astrophysical problems?

2 Themes

As described in Mihalas' introductory talk, radiation can affect an astrophysical plasma, flow, or object in several fashions. First, it can influence the kinematics through ionization, dissociation, and other gas-phase processes that depend on chemistry, ionization state, or excitation. But second, it can influence the dynamics of the flow, through deposition of momentum. Examples of the latter are shock waves, accretion disks, novae, supernovae, and hot-star winds. One can, therefore, divide the topics at this meeting into "active" and "passive" classes of radiation hydrodynamic problems (Table 1). The term "active" implies dynamic pressure from the radiation, whereas the term "passive" allows the radiation to affect the state of the gas, particularly its spectral emissivity, without affecting its motion appreciably.

Before addressing the individual topics, I have tried to find several themes that unify the broad diversity of talks at this meeting. Besides the obvious commonality in studies of radiation energy and momentum transport, most talks addressed one or more of the following three questions: (1) When does radiation push but not heat? (2) What are the instabilities introduced by the radiation? (3) Has the perfect computer code been developed? I will discuss each of these in turn.

Table 1. Classification of Topics

Active Sources	Passive Sources
Novae	Proto-stellar Objects
Supernovae	Supernova Remnants
X-ray and γ-ray Bursters	H II Regions
Pulsating Variable Stars	Radiative Shock Waves
Accretion Disk Tori (thick)	Accretion Disks (thin)
O-star Winds	Interstellar and Intergalactic Matter
Quasar Outflows	Quasar Broad-Line Clouds

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a) When does radiation push but not heat?

Answering this question is equivalent to placing the problem into the two categories of Table 1. If one separates the opacity into portions due to scattering (κ_{sc}) and pure absorption (κ_{abs}), then one can generally say that radiation will push but not heat when

$$\kappa_{sc} >> \kappa_{abs} \quad . \tag{1}$$

If the radiation field is a blackbody, this criterion can be recast into a condition on energy densities ($U_{rad} \gtrsim U_{matter}$), or

$$T_{keV} \gtrsim 2\ \rho_g \tag{2}$$

where T_{keV} is the radiation temperature in kilovolts and ρ_g is the mass density in g/cm^3. Evidently X-rays and γ-rays are far more likely to involve momentum transport than lower energy photons.

In many situations, the radiation is far from Planckian, yet radiation is important in the dynamics. Two cases were frequently discussed: Compton scattering and line scattering, as in the context of O-star or quasar winds. Two other cases that were not discussed are interstellar dust grains and continuum edges. Particularly in dark interstellar clouds, the scattering opacity of dust grains and their ability to re-radiate absorbed energy into optically thin wavelength bands makes them an ideal example for radiation hydrodynamic techniques.

b) Instabilities

Most of the astrophysical objects discussed here involved some type of instability, and many of these are related. Some involved the electromagnetic force (EM), and some the strong or gravitational force. After conversations with several participants, I realized that a few even involve the weak force. (See Table 2.)

Table 2. Instabilities

Thermal (Interstellar medium or Quasar broad-line region phase transitions)
Disk and Cepheid (Ionization zones)
Nuclear Burning (Novae, Supernovae Type I, X-ray bursters)
Gravitational (Core collapse, Supernovae Type II)
Magnetic and Plasma Kinetic (Radio pulsars, Solar flares)
Pair-Plasma Breakdown (Active galactic nuclei)
Line-Driven Wind (Hot stars)
Line-Driven Rayleigh-Taylor (Quasar broad-line clouds)
Neutronization (Formation of neutron stars by inverse-beta decay)

To illustrate the similarity between several of these instabilities, let us discuss the familiar double-valued equilibrium curve (Fig. 1a) describing thermal phases of interstellar matter (or gas near a compact X-ray source such as a neutron star or quasar nucleus). The temperature T of a gas in thermal, ionization, and pressure equilibrium, depends on the source of the ionizing UV/X-ray radiation. For gas of hydrogen density n(cm^{-3}), a distance r from a source of luminosity L(ergs s^{-1}), we define an "ionization parameter," Ξ, equal to the ratio of radiation pressure to gas pressure [1,2],

$$\Xi = \frac{P_{rad}}{P_{gas}} = \frac{(L/4\pi r^2 c)}{(nkT)} \quad . \tag{3}$$

For $\Xi < \Xi_A$, an increase in Ξ results in more ionization and higher temperature. However, when Ξ increases above Ξ_A, the photoionization is so great that the dominant coolants (primarily Li-like ions, such as C IV, N V, and O VI) are stripped

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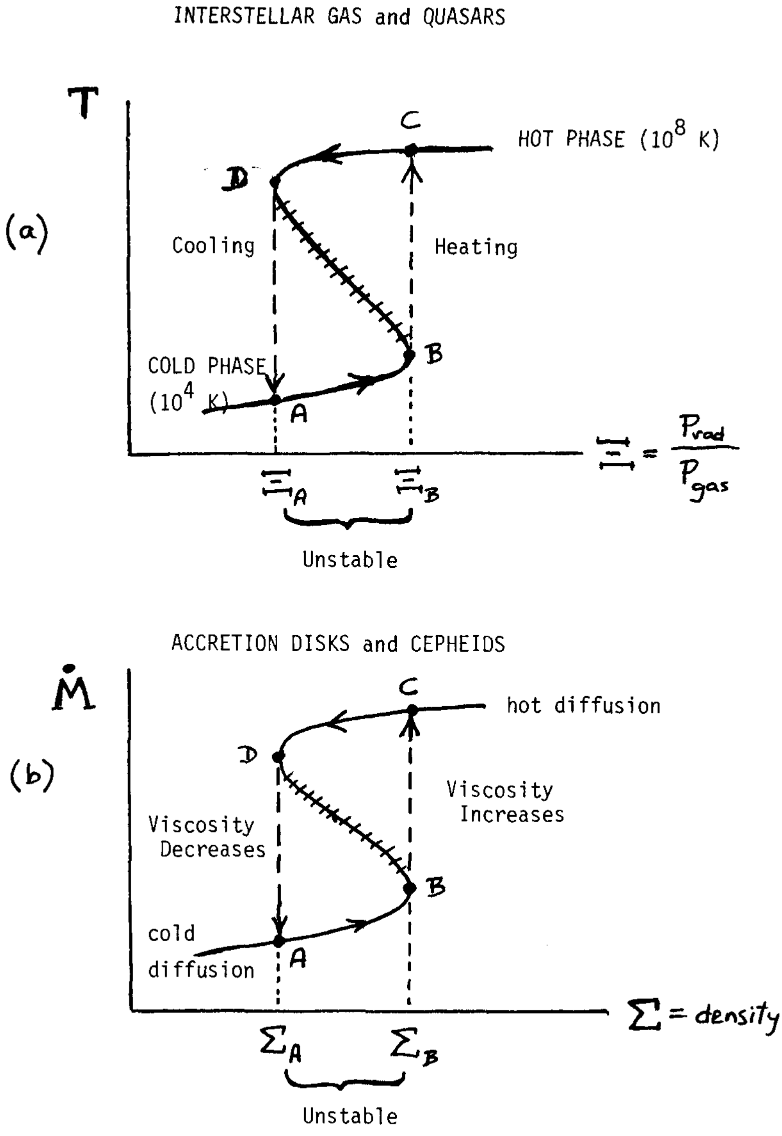

Fig. 1. Equilibrium phase diagram for: (a) interstellar or quasar photoionized gas; (b) accretion disks.

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of their bound electrons and the locus of equilibria bends on itself. For $\Xi_A < \Xi < \Xi_B$, there are three equilibria; a "cold phase" around 10^4 K, a "hot phase" around 10^8 K, and an intermediate-temperature phase which is thermally unstable. Perturbations away from the curve in this intermediate regime either run away to 10^8 K, or cool to 10^4 K; the gas is thermally unstable. When $\Xi > \Xi_B$, the gas is again thermally stable, and can exist only in the hot phase.

We can therefore identify the cold phase with clouds in interstellar space [3,4] or broad-line clouds [1,2,5] in an Active Galactic Nucleus (AGN). The hot phase is the intercloud medium needed for pressure confinement. Transitions between hot and cold phases occur on a heating or cooling timescale, and consist of alternate cycles around the phase loop, ABCD.

Figure 1b shows the morphologically similar phase diagram for the accretion disk instabilities discussed at this meeting [6,7]. In this case, T and Ξ are replaced in the diagram by the mass accretion rate $\dot{M}$ and the disk's surface density Σ. Because the disk structure and $\dot{M}$ depend on the viscosity, the equilibria are multi-valued, with the same type of cycles as the interstellar thermal instability. The "kink in the curve" morphology is typical of a class of instabilities in Catastrophe Theory. Also, the interaction of the hydrogen ionization zones with the disk thermodynamics is similar to Cepheid variables.

c) The Perfect Code

Perhaps the most striking impression I have obtained at this meeting is of the technical complexity of the computer codes used to study radiation hydrodynamical problems. And yet the "perfect" code is far from being developed. Although non-LTE stellar atmospheres models, supernova nucleosynthesis and atmosphere models, and hydrodynamic codes exist, the new requirements of three-dimensional flow, radiative transfer, line blanketing, shock waves, and fluid instabilities create unprecedented demands on the computers. Consider the unsolved technical problems of three examples:

Hot Star Winds

- We do not know the EUV continuum (backwarming of atmosphere by stellar wind).
- What effect does multi-scattering of resonance lines have on the wind?
- What is the ionization state of the ions that dominate the resonance lines?
- What is the effect of shock waves on the flow? On the ionization state?
- What is the nonlinear state of these shock waves?

X-Ray Bursters

- How does one model spatial and frequency transport of radiation?
- How does one handle an advective plus diffusive luminosity exceeding L_{edd}?
- How does one patch together the nuclear burning region with outflowing wind?

Accretion Disk Tori

- Are the analytic approximations of Begelman, McKee, and Shields [8,9] appropriate?
- What is the effect of two-dimensional flow off the Compton-heated disk?
- Does the flow shock?
- What is the effect of thermal conduction ($T_i \neq T_e$)?

The implication of these technical problems is that we have a ways to go before the model builders can make strong statements about the nature of the astrophysical sources. Certain models for supernovae cannot be ruled out, applications of X-ray bursters to galactic dynamics cannot be regarded as secure, and conclusions

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about the mass of AGN black holes cannot be drawn from Eddington limits until many of the technical models are improved. This will almost certainly require a new generation of computers, coupled with better atomic and nuclear data and some innovative coding.

3 Review of Selected Topics

The papers and talks at this meeting fall conveniently into four major areas: (1) Stars; (2) Supernovae; (3) Novae and Bursters; (4) Quasars and AGN's. In this section, I give a heavily selected and personally biased view of the current work in Radiation Hydrodynamics relevant to these areas. And, as is appropriate for a summary paper, I have tried to point out the major unsolved problems and some areas of broad application to astronomy. Because I haven't the answers to these problèms, I will simply pose them in a casual format.

a) Stars, Stellar Pulsations, and Stellar Winds

Protostars. Understanding protostars certainly involves difficult problems in hydrodynamics (core collapse, accretion of envelope, rotating fluids, and molecular outflows), but it is not clear that radiation hydrodynamics is important. The momentum flux in these protostellar outflows, $\dot{M}v$, far exceeds that in the stellar radiation field, and magneto-hydrodynamics may be more important. Star formation can probably be triggered by several mechanisms: gravitational (Jeans) instability, thermal instability, or a combination of shock-induced thermal and Jeans instability [10]. Primordial star formation may also involve interesting chemistry in the intergalactic medium [11,12]. The important unsolved problems in this area include:

- How to collimate and accelerate protostellar outflows?
- Are magnetic effects important in outflows, or do rotation and a density gradient suffice?
- What determines the initial mass function (IMF) of stars and what sets the maximum mass?
- How does the IMF depend on the physical environment of the galaxy or cloud?

Pulsating Variables. Radiation plays an important role in the pulsations of most stars, contributing 10-30% of the total pressure. Sophisticated codes exist to model the radial and non-radial modes of these stars, but two major technical difficulties remain:

- Because opacity tables are incomplete and insufficiently reliable, pulsations cannot be used as diagnostics of stellar interiors.
- Shocks in stellar atmospheres are not yet understood.

Until atomic physics progresses to the point where photoexcitation and photoionization cross sections are accurate to approximately 10%, the opacities will remain a shortcoming of these models. Coupling the pulsations to a dynamic atmosphere is likewise a technically difficult problem ideal for a radiation hydrodynamic approach. As evidence of the uncertainties in stellar pulsation theory, one need only mention β Cepheid stars, whose pulsation mechanism is not understood, despite more than five candidate theories.

Solar Flares. A major problem in this field concerns the origin of the X-ray and γ-ray emission. Does it come from a thermal wave or a non-thermal particle beam generated by magnetic instabilities? Are radiative shocks important in the sun's atmosphere? Understanding the small-scale magnetic flares on the sun is important before we can believe the scaled-up mechanisms for the flare stars seen with the IUE and Einstein satellites. Coronal activity, rotation, and magnetic fields appear to be coupled, but the details are obscure. Once again, though, the problem may be more magneto- than radiation-hydrodynamics.

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O-Stars and Wolf-Rayet Stars. Without a doubt, the single overriding problem in this area concerns the effect of the shock waves in the wind, believed responsible for the X-ray emission from O stars. We know instability exists [13,14] but we do not understand the nonlinear state of the shocks. What is their effect on the velocity law, the ionization state, and the stellar atmosphere? Do the shocks destroy the underlying Castor-Abbott-Klein [15] radiation-driven wind? Some of the broader questions are:

- Is the wind solution non-perturbative, requiring a radiation hydrodynamic model?
- Can wind blanketing and backwarming explain the momentum flux, $\dot{M}v > L/c$?
- What are the effects of winds on evolutionary tracks and H-R diagrams?
- How do stellar winds affect their environment (interstellar medium)?
- Is the IMF of massive stars variable in different galaxies?

b) Supernova and Supernova Remnants

Supernova Explosions. Supernovae are classified into Type I (no hydrogen lines) and Type II (hydrogen seen) according to their spectra, although they are morphologically associated with stellar Population II (low-mass, old stars) and Population I (young, massive stars), respectively. Models for Type I's as radioactive explosions of white dwarfs in binary systems and of Type II's as core collapse and bounce in massive stars are widely regarded as correct. The fate of intermediate mass (6-12 $M_\odot$) stars is still uncertain. Nevertheless, major problems exist in this field.

- What is the minimum mass star that explodes as a Type II supernova?
- Does a Type I supernova involve a deflagration or detonation?
- Is the white dwarf binary model correct, or are double white dwarfs involved?
- Can the neutrino shock revitalization model work in Type II's?
- How will the new ${}^{12}_{6}C(\alpha,\gamma){}^{16}_{8}O$ reaction rates affect the Fe cores?

In a broader sense, it can be said that we do not understand what stars make what supernovae, despite large amounts of circumstantial evidence involving historical SN, SNR's, pulsars, and X-ray sources. We certainly do not understand the nucleosynthetic yields, theoretically or observationally. The solution of these problems affects all of astronomy, from chemical models of the galaxy to studies of the interstellar medium and starburst galaxies. Enormous computing facilities will be required, as well as nuclear data, hydrodynamic codes, and basic knowledge about convection, turbulence, and other fluid instabilities that arise in the burning layers and envelopes.

Supernova Spectra. For Type I supernovae, the model atmosphere problem appears difficult, but solvable. The outer layers are probably moving homologously ($v \propto r$), but the radiation transfer is complicated by an enormous (and uncertain) range in abundances, ionization states, and excitations. Non-LTE models are needed. Major problems are:

- Confirm the ${}^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ beta decay scheme spectroscopically [16]
- Understand the source of the UV deficit
- Develop model templates for absolute brightness from spectral lines
- Understand the role of the Rayleigh-Taylor turbulent flame fronts.

The payoff to these technical difficulties may well be that Type I SN will become the most reliable distance indicators for the Hubble constant. The current best value of $H_o \approx 40$ km/s/Mpc with this method cannot yet be accepted as reliable.

Supernova Shocks. Following the SN explosion, we now know that the blast wave and shocks interact strongly with the circumstellar and interstellar medium. Before

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we can understand the dynamics, spectra, and abundances from these objects, we must solve several problems:

- What produces the radio emission and can we use it to find the age and rate of supernovae?
- What is the density structure of the reverse-shocked ejecta in young supernova remnants? How does it affect the X-ray emission and heavy element abundances determined from the X-ray line emission?
- Can we "calibrate" the star formation rate in Starburst galaxies from their optical and radio emission?

c) Novae and Bursters

Novae and bursters share a common mechanism on different collapsed objects. One might expect some similarities, although because the gravitational potential is much deeper for a neutron star than for a white dwarf, the maximum luminosities may differ. There are exciting new observational developments in this field, with implications for nucleosynthesis and galactic structure. Perhaps the most controversial are the discovery of possible 4.1 keV Fe features in two bursters (suggesting a gravitational redshift $z = 0.6-0.7$) and the suggestion that bursters may be used as distance indicators (giving a distance to the galactic center of 6-7 kpc). Questions raised at the meeting include:

- Are "neon novae" the cores of 8-12 $M_\odot$ stars?
- Is there a significant difference between the masses of field white dwarfs and white dwarfs in binaries? If so, why?
- Is the maximum mass of a burster 1.05 L_{edd}? Are they "standard candles"?
- Does the burster distance to the galactic center create an inconsistency with distances determined by RR Lyraes and globular clusters?
- Is the 4.1 keV feature in burster spectra real? If it is Fe, where are Si and S? Is the gravitational redshift interpretation consistent with realistic models of neutron stars?

Theoretically, an important problem in bursters is to match the nuclear burning zone with the outflowing wind. It is important to confirm the upper luminosity limit on bursters [17], since their use as standard candles depends on this assumption. Two other important problems concern the nature of the accretion disk instabilities (two-phase or viscous instability at the Lagrangian point), and the nature of the rapid Type II bursts.

d) Quasars and AGN's

The nature of the central engine, its mass supply, the trajectories of broad emission-line clouds, and the acceleration and collimation mechanisms for radio jets are still controversial. Many AGNs have P-Cygni features or blue-shifted absorption lines reminiscent of O-star winds (Fig. 2). We still do not know whether this outflow is produced by radiation pressure or energetic particles. An even broader question is whether the quasar activity affects the properties of the entire galaxy. What are the lingering effects in spiral galaxies today? Among the major questions addressed at the meeting were:

- Are the broad-line clouds on non-virial trajectories? If so, what is the mass of the central object?
- Is there a quasar wind? What are the instabilities of broad-line clouds accelerated by this wind?
- What is the mass supply to the central object (black hole)? For a 10^{46} ergs/s quasar, one needs 1 $M_\odot$ yr^{-1} if the acceleration is 10% efficicent.
- What forms and collimates the radio jets? Are magnetic fields important?

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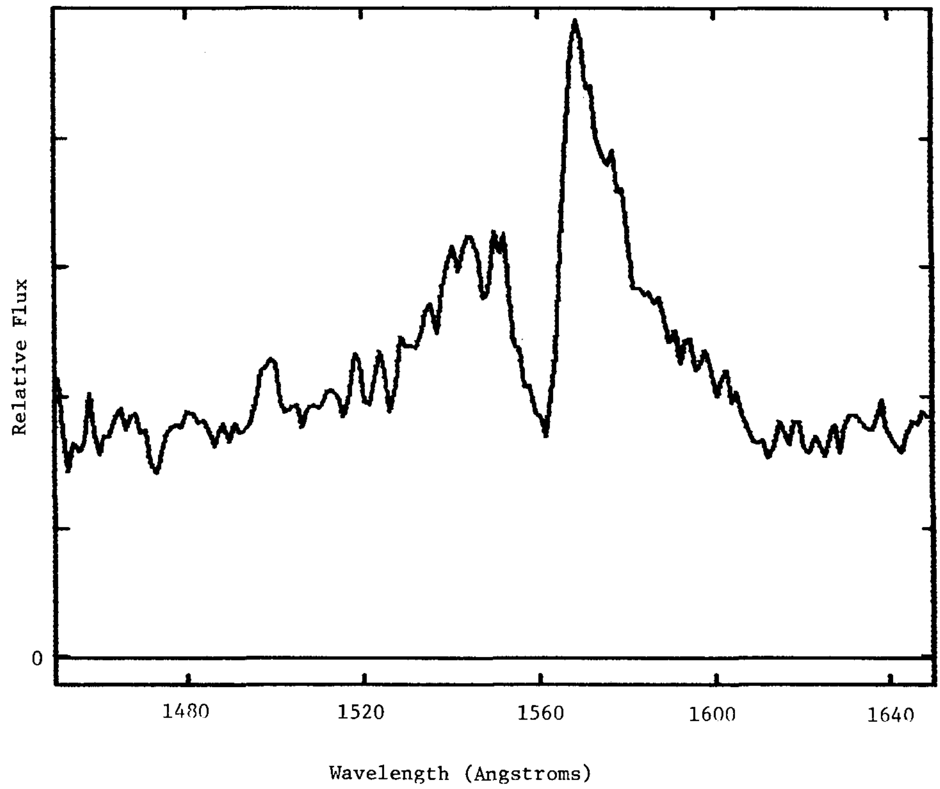

Fig. 2. IUE spectrum of the C IV λ1549 line in the Seyfert galaxy NGC 3516. Notice the blue-shifted absorption.

An ideal case for radiation hydrodynamic studies is the interaction of the UV/X-ray radiation from the central object with stellar atmospheres in the galactic nucleus [18-20]. One can easily demonstrate that the fluxes from a central black hole will have significant effects. Radiative heating and radiation pressure at the limbs of red giants can produce ablative X-ray winds (Fig. 3), and may provide a significant mass supply to the quasar. This mechanism has obvious feedback characteristics, and may be especially important during periods of X-ray variability.

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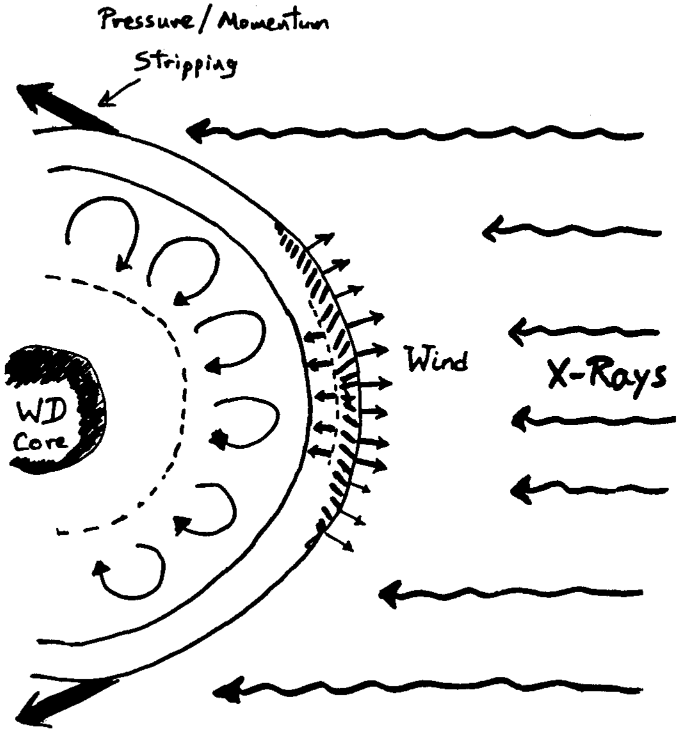

Fig. 3. X-rays from the central engine in an AGN can produce an ablative wind and stripping of gas at the limb [18-20].

4 SUMMARY

As mentioned earlier, the most striking impression that I was left with after this meeting was the complexity of the problems being addressed and the questions being asked. In the "olden days," such problems were answered with the vaguest sort of handwaving. Today, we are on the threshold of actually answering them with large computers. There is still an acute need for a new generation of modeling techniques and for scientists to interpret them. The output must be synthesized into a new understanding of how fluids and radiation fields interact in the nonlinear regime.

The problems in astrophysics today are often two- and three-dimensional; they involve fluid dynamics, instabilities, atomic physics, and nuclear physics. In many areas, they probably require knowledge in subjects many astrophysicists have been reluctant to consider in proper detail -- convection, turbulence, magnetohydrodynamics, and even neutrino transport. Perhaps our next meeting should be on "Radiation-Magneto-Lepto-Hydrodynamics"! I would like to conclude with an amusing look at the conference (Fig. 4), and with thanks to the organizers for an efficient and educational meeting.

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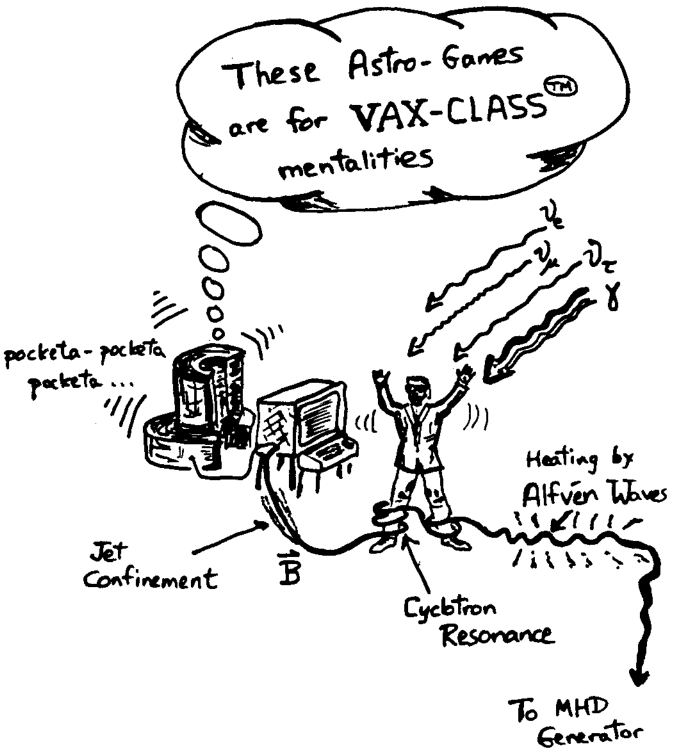

Fig. 4.

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