Introduction and Overview

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The theme of this Colloquium is radiation hydrodynamics in and around stars and other compact bodies. To open our discussions, I would like to offer some rather elementary remarks about the role played by radiation in astrophysics.

It is probably true that most astronomers view radiation primarily as a diagnostic tool. After all, the only access we have to astrophysical bodies (with a few exceptions inside the Solar System) is the photons we capture from them. And so an immense effort has been devoted to the development of techniques for converting raw information about the spatial, temporal, spectral, and polarization variation of the observed radiation field into knowledge about the physical structure of the object that produced the radiation. There are many difficult challenges, both observational and theoretical, to be met in this process, and the field is in a state of rapid development today, and will remain so for the forseeable future. Nevertheless, in the context of this conference it is worth emphasizing that in the diagnostic problem radiation plays an essentially passive role; it is merely the tool used to analyze the situation.

At a somewhat deeper level one can recognize that radiation can influence the kinetics of a flow, that is, it can influence (or even determine) the internal state of the material in the object being observed. Somewhat old-fashioned examples of this aspect of the problem are the well-known radiatively-driven departures from LTE in stellar atmospheres and planetary nebulae. More interesting examples in the context of this conference are found in phenomena such as ionization fronts, dissociation fronts, deflagration waves, and ablation fronts, where radiative input radically changes the thermodynamic state of the fluid on scales essentially unrelated to those characteristic of the fluid flow itself. Such effects can have profound consequences for the development of the flow.

But perhaps most interesting of all, radiation can directly drive the dynamics of a flow. Specifically, radiation may dominate: (1) energy exchange/deposition in the fluid, for example in waves and shocks; (2) momentum exchange/deposition in the fluid, for example in stellar winds or accretion disks; or (3) both energy and momentum exchange, for example in supernovae (where both photons and neutrinos may act as the dominant transport mechanism at different phases of the implosion-explosion episode).

One can begin to develop a qualitative feeling for the dynamical importance of radiation from the ratio

$$R = \frac{\text{material energy density}}{\text{radiation energy density}} = \frac{\frac{3}{2}\,NkT}{aT^4} = 2.8 \times 10^{-2}\,\frac{N}{T^3}\,, \tag{1}$$

which shows that radiation becomes the dominant component of a radiating fluid at high temperatures and/or low densities. Specifically $R \approx 1$ when $T_{kev} \approx 2\,\rho^{1/3}$ where T_{kev} is the temperature in kilovolts ($\sim 10^7$ K) and ρ is the density in grams/cm^3. Thus we see that once temperatures reach a kilovolt or so, radiation dominates even at the densities prevailing in stellar interiors. Put another way, if we observe such high-temperature X-radiation from an astrophysical source, we can be reasonably certain that at some point radiation played a crucial role in the dynamics of the event that produced the radiation.

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In the same vein one can get a feeling for the importance of radiation as a transport mechanism from the Boltzmann number:

$$\mathrm{Bo} = \frac{\text{material enthalpy flux in flow}}{\text{radiative flux (open boundary)}} = \frac{\rho\, c_V\, T\, v}{\sigma T^4} . \tag{2}$$

By some simple algebra one finds that Bo ~ (v/c) R. In typical astrophysical applications (v/c) << 1, hence radiative energy transport strongly dominates even when the radiative energy content of the fluid is small. (This remark strictly applies only at an open boundary. In an opaque medium, say inside a star, we must use the net radiative flux, characterized by the effective temperature T_{eff}, not the local temperature T. In this regime advective energy transport by fluid motions may easily overwhelm radiative transport.)

From ordinary laboratory experience we tend to think of radiation as resulting from the hydrodynamics, for example the radiation produced by exciting the downstream gas in a strong shock tube (an astrophysical analogue would be a radiating shock in the interstellar medium, as in a supernova remnant such as the Veil Nebula). But in doing astrophysical work it is far more fruitful to be constantly alert to the possibility that radiation is creating the flow. The moment one looks, one finds a truly fascinating variety of phenomena. For example, one can view H II regions as radiation-driven explosions, exhibiting many of the same characteristics as terrestrial fireballs around intense explosions. Pulsating stars are essentially radiatively-driven thermodynamic engines, resulting from an unstable coupling between the net rate of transport of radiation and material properties (particularly opacity) which respond to changes in local conditions produced by changes in the transport rate. Clouds of interstellar material can be driven to high velocities by radiative rockets or collapsed into protostars by radiatively-driven implosions. There are complex nonlinear feedback loops between radiation and hydrodynamics in, say, X-ray binaries with radiatively-driven accretion flows (spillover through the Roche lobe). And a bewildering variety of exotic (which merely means somewhat unfamiliar, and therefore not yet well understood) phenomena occur in and around the central engines that power active galactic nuclei.

As we shall see in the course of the next few days, there is a significant element of radiation hydrodynamics in each of the classes of objects to be discussed at this meeting: (a) Protostars, (b) Stellar Jets, (c) Pulsating Stars, (d) Solar/Stellar Flares, (e) Stellar Winds, (f) Supernovae, (g) Novae, (h) X-ray sources, (i) Accretion Disks, (j) X-Ray and γ-Ray Bursters, (k) Active Galactic Nuclei, and (l) Extragalactic Jets. In fact, radiation hydrodynamics also plays a key role in cosmology (but that topic is clearly outside the peerview of this conference — which already is much broader than some of the organizers had originally imagined!).

Yet it is highly probable that many of the people working in most of these areas are not particularly aware of having been doing "radiation hydrodynamics." Perhaps one reason is that astronomers typically tend to focus their attention on their pet objects, and notice the underlying physics only secondarily, if at all. In addition the range of phenomena (and likewise the variety of objects) is so large that each one of us here will probably be familiar with (hence think we are interested in) only a small subset of the whole. Indeed these are the very considerations that motivated holding this conference, and it is worthwhile to ponder briefly what the goals of the conference might be for its participants, and what readers of the conference proceedings might hope to extract from them.

My own view is that to a large extent this meeting should serve as a tutorial for the participants, and, I hope, through the proceedings for a future generation of students. I think that we should all therefore aim at broadening our own personal intellectual horizons, an act that will foster interdisciplinary understanding and promote interdisciplinary cross-fertilization. Further, we should make a strong attempt to break down the walls of specialist jargon that tend to isolate us. It is essential for us mutually to discover that what he might call a "working surface," she might call a "stagnating D-front;" what you might call a "rocket," I might call an "ablation front;" and so on. In addition we should try to share scientific experience: it will aid the progress in all of our specialities to find out that a problem confronting us in one context has already been addressed and solved effectively in another, and that we can adapt our colleague's techniques to do our own work better. More important, we should try to recognize and reveal the underlying unity of seemingly disparate fields by pointing out and emphasizing common physics.

The main goal of our efforts should be to share our insights with one another. And here I cannot resist offering a metaphor. One can think of the process of learning something about the real world as being like a climb up a steep mountain. As we start up the slope we must first clamber over a very rocky field of "information," that is, the "what, when, where, ..." of what we are studying. I think that today we find ourselves virtually swimming in information: the rain of bits seems relentless, and the true nature of the object(s) of our study remains cloaked in cloud. Many of us give up at this stage. But if we climb a bit higher, we can sometimes organize the information into "knowledge" and begin to understand something about the "how" of the phenomena we are studying. We then have made some progress. If we continue to climb upward in the cold wind of knowledge, we eventually begin to learn some of the limitations of what we "know;" we discover the "but" to the "what, ..., how." We have arrived at a level we can call "wisdom." Some get discouraged and retreat at this point. But a few persist in climbing, eventually reach the summit, and then get to stand in the warm sunlight of "insight." It is there that we have the "Ahah!" experience that pulls it all together and shows the way to new paths for research.

The point of this little metaphor is that insight is hard-won and therefore precious. We thus should be mindful of sharing it when possible, and we should pay close attention to the tools we use to acquire it. In this vein I would like to make some remarks about one of the important tools many of us here use in our work in this area (and others), namely the computer. I suspect that a personal reminiscence parallel to this one could be made equally well by, say, an observer. In both cases we get a little perspective on the past, and a view of prospects for the future.

The first computer I encountered was SWAC (the National Bureau of Standards Western Automatic Computer) while I was a student at UCLA. Currently I can work on a Cray X-MP. A rough comparison of the capabilities of these two machines is shown in the table below:

SWAC (1957)	X-MP (1985)
10^3 FLOPS	$10^{8.5}$ FLOPS
$< 10^2$ words of random memory	$10^{7.5}$ words of memory
Machine language coding	Vectorizing compiler
Punched tape or cards	Computer files
No remote access	Extensive network

One sees that in a fraction of my professional lifetime I have experienced about a factor 300,000 both in speed and in store. That's an interesting number: it means that today I can perform in one second a calculation that in 1957 would have taken 3 ½ days (and that only if I could have had exclusive access to the machine - which I couldn't - and if the machine could have stayed up that long - which it wouldn't). In the course of the next decade we can reasonably expect a further factor of 10^3 to 10^4 increase in computational capacity as a result of improved processor speeds and, more important, parallel processing. This will mean that I can do in a second a calculation that would have taken a century - that is, a time longer than my lifetime - on SWAC. Similarly, when I did my thesis work (the first computational astrophysics thesis at Caltech) I had to work the graveyard shift (midnight to 8 am)

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on a computer located several miles from my home and office. The only communication was by transporting many boxes of IBM cards in my car. To say the least, this was an extremely hard and wearing regimen. By contrast, today I can work on a terminal or a microcomputer in the comfort of my own office or home, which obviously increases one's efficiency and accelerates progress.

Why are these remarks important? Because they emphasize that if people have to wait too long for their answers, they get: (a) bored, (b) fatigued, (c) diverted, or (d) old; in fact if they have to wait too long they simply die. If people know ahead of time that a calculation will take too long, then they don't even try it, no matter how interesting it may be. In any event the work doesn't get done; the hypothesis doesn't get tested; the idea never becomes a result.

In my opinion the real significance of the gains in computational speed discussed above is that they facilitate the translation of human creativity into productivity. They thus enhance our most important human resource. And other tools are on the way: smart symbolic maniputators; versatile graphics; artificial intelligence devices, and so on. It should be an exciting era, particularly if we can couple the energy and imagination of our youngest colleagues to the insights gained by older, more experienced workers who have explored the frontier up to the perimeter where we stand today.

Finally, in closing let me stress that it is extremely important to make an effort to educate those who fund our research so that they will understand that while the machines we use and need may be "expensive," human creativity is irreplaceable. The human race may get a von Neumann only once per century or so. The last time we did, he could translate only a tiny fraction of his total creativity into productivity because the tools he needed were not there yet: he had to invent them. The next time we will be better prepared!

So let me invite you all again to spare no effort to share experience and insight, to ask penetrating questions and respond with wise answers, and to help us all gain a broader and more complete conception of the work in which we are engaged individually, and how it relates to the work of others.

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