

8. Radiation Hydrodynamics in Astrophysics

8.1. Introduction

Led by several high profile satellite missions, innovative ground-based instrumentation and new large telescopes, astrophysics stands at the threshold of revolutionary discoveries in the next decade. The quality of the scientific output that will flow from these efforts is in most cases inexorably linked to a deep understanding of how light interacts with matter. The physics of this process is the study of radiation hydrodynamics, an interdisciplinary field of study that includes theoretical, numerical, laboratory, and observational efforts, and spans an enormous range of objects and physical conditions.

Radiation routinely plays a central role in the *dynamics* of astrophysical systems, and is frequently the dominant mode of heat transfer, controlling the degree to which fluids behave non-adiabatically. Ionizing photons can substantially alter the balance of ionic species in a plasma, a key spectral signature in astrophysical observations. Thus, by means of these two effects, the equation of state of astrophysical fluids is almost always governed by coupling to radiation, so that fundamental dynamical parameters such as the speed of acoustic waves are determined by the fluid's interaction with light. Radiation can also be a major agent of momentum transfer, making the forces exerted by photon fluxes the primary driver of fluid motions. Even some of the few exceptions to these generalizations (e.g., when heat is transferred to neutrinos rather than photons) involve very similar processes, so that their analysis may also be placed under the rubric of "radiation hydrodynamics".

Although in these regards, astrophysical systems can be quite different from terrestrial ones, there are genuine similarities to laboratory plasmas. Heat may diffuse within laboratory plasmas by the motion of electrons and ions, but magnetic confinement means that only photons (or neutrons) can actually carry heat away, in magnetically confined plasmas. In radiation-driven inertial confinement fusion systems, in fact, radiation is the dominant carrier of heat. Linked by these qualitative resemblances, the tremendous range of conditions found in astrophysical plasmas can illuminate laboratory plasma physics by exhibiting different physical mechanisms in extreme form. Conversely, for those special cases in which the conditions of laboratory plasmas can be matched to astrophysical plasmas, we are given the rare privilege (for astronomy) of being able to *experiment* rather than merely observe.

8.2. Astrophysical Environments

There are a very wide range of phenomena in astrophysics where radiation hydrodynamics plays a dominant role in the dynamics. In this section, we list a number of contemporary astrophysical problems in which issues of radiation hydrodynamics are especially important.

8.2.1. Exoplanets

Examples of the intimate connection between radiation hydrodynamics and major current astrophysical programs abound. For example, consider the new field of exoplanets. In this, the first decade since radial velocity surveys around other stars uncovered the first planets around other stars, the number of such planets has soared to over 400. With such a large sample, astronomers now face the reality that the planets which populate our Galaxy can differ markedly from those in our solar system. The notion that all solar systems are organized with small rocky planets close to their stars and large cool gas giants at large distances has given way to the reality of a much richer and intriguing scenario that includes Jupiter-sized planets that orbit closer to their host stars than Mercury does around our Sun. In these cases, the intense radiation field from the star will alter the chemistry of these dense planetary atmospheres, determine the cloud structure, and drive large-scale flows in their atmospheres.

8.2.2. *Star formation*

Stars are born in dusty molecular clouds. Because dust opacity in the infrared is considerably greater than that of electron scattering, once the first stars in a region light up, their radiation drives significant forces in the surrounding gas. Young stars can also photoionize and heat the gas around them. The most massive have surface temperatures so high that they produce substantial UV radiation; all young stars exhibit enhanced X-ray activity. Increased ionization strengthens the coupling of the gas to embedded magnetic fields; this stronger coupling can both enhance accretion onto forming stars by mediating angular momentum transport and retard it by trapping the magnetic flux or strengthening magnetically-driven winds. Higher temperature raises the pressure, resisting gravitational collapse, but also possibly accelerating accretion by supporting higher amplitude MHD turbulence. Irradiation may also tilt the size distribution of interstellar grains, changing the total dust opacity. We know that these effects can be important in setting the pace and character of star formation because we can see it happening---there are now stunning examples of accretion disks around forming stars photoevaporated by the young massive stars in their proximity.

Much of current research centers on studying how disks of dense gas and dust evolve into planetary systems. Observations have shown that these disks often lack near-infrared emission, a sign that they do not extend all the way to the star, but are truncated at some radius, probably determined by where radiation from the star sublimates the dust in the disk. There is even evidence for a raised inner rim of these disks, as the radiation heats the material there and causes it to expand. Radiation also plays a key role in determining how disks transfer angular momentum outward, and how material at the disk midplane circulates. In areas where radiation penetrates enough to partially ionize the gas, large-scale magnetic fields will couple the gas to the overall motion of the star and disk, leading to system where disk material can funnel onto the star along field lines, and be ejected from the system in a collimated jet. The physics of the disk/jet system is a fundamental

one that occurs throughout astrophysics in X-ray binaries, active galactic nuclei, and possibly even planetary nebulae.

8.2.3. Solar structure and composition

The sun continues to provide new challenges and new insights for stellar physics, despite the fact that it is one of the best studied and best understood objects in the universe. The sun's proximity to earth makes high accuracy measurements feasible, raising the bar for solar models. Understanding solar structure is a compelling goal by itself, but it also has broad ramifications far beyond the curiosity of solar specialists. The sun provides the "gold standard" for models used to describe every star we see and the demands on the accuracy of solar models are consequently high. Furthermore, the composition of almost all stars and many other astrophysical objects are calibrated by solar models. Thus, the total oxygen inventory available to form water (H_2O) in the universe is determined by solar research. How well we understand the distribution and scope of water, the fundamental building block of life, depends on how well we understand the sun.

The sun is the best studied star and helioseismology is the most powerful tool used in those studies. Helioseismology enables precise tests of how accurately solar models predict the solar structure and, in particular, how well they predict the interior radiation transport. In the mid-1990s the internal structure of the sun was believed known because models agreed with helioseismic observations. More recently, increasingly sophisticated analysis of photospheric spectra has led to major revisions in the solar composition and solar models now significantly disagree with observations. Is this problem because even the most refined photosphere models are in error? Is it because the theoretical opacity models lack sufficient accuracy? Or is it because the physical approximations used in the solar models do not capture all the essential science? It is worth remembering that stellar interior models use input information from models for the properties of stellar matter and those material property models have never been experimentally tested at stellar interior conditions. The combination of precision observations, detailed models, and new ability to measure the properties of stellar interior matter in terrestrial laboratories provide an opportunity to answer these questions. The results will refine our physical pictures for the internal structure and chemical composition of the sun and most other stars. Furthermore, the solar composition is often assumed to prevail in other objects, for example, in exoplanet atmospheres. Thus, a refined understanding of the sun has broad implications for astrophysics.

8.2.4. Radiation from massive stars

Massive stars have disproportionate influence in the evolution of the Universe. The energy they inject into surrounding gas, both during their lifetimes and in the supernova explosions by which they die, is a major determinant of the motion and pressure of interstellar gas in galaxies; when many supernovae occur within a relatively brief time, they can jointly drive large-scale outflows that expel much of the gas possessed by the galaxy, potentially cutting off any further star formation for very long times thereafter. In addition, the majority of the most abundant elements (after H and He) are synthesized in massive stars. Radiation from massive stars has a profound influence on nearby disks that are in the process of forming. Examples of such objects abound in the Orion Nebula,

where we see disks being photoevaporated by intense ultraviolet radiation from nearby O stars. Such a process may have occurred in our own Solar System, as evidenced by the missing gaseous envelopes around the outer gas giants Uranus and Neptune. Understanding the evolution of massive stars is therefore of special importance to many aspects of astrophysics.

Radiation hydrodynamics plays a crucial role in the lives of massive stars because they generically emit winds, driven by radiation forces, that over the course of their lifetimes carry off a large fraction of their initial mass. Just how much mass is lost is of great importance, of course, to the character of the ultimate supernova. We have good evidence, both observational and theoretical, that the forces are expressed through scattering of the stellar UV continuum by a large number of atomic resonance lines, but there remain very large uncertainties about the operation of these winds because the technical problems are severe. The associated radiation transfer problem is both multi-dimensional and frequency-dependent, and the character of the frequency dependence depends on the local velocity of the fluid. Moreover, the ionization balance, which determines the line opacity, is also controlled by the passage of photons through the moving fluid, so both the continuum transfer and ionization balance problems must be solved as well.

8.2.5. Radiation in relativistic astrophysics

In ~15% of the quasar population, very broad absorption troughs ($\sim 10,000$ km/s) are seen to the blue of the systemic redshift in a number of ionic resonance lines (commonly CIV ~ 1550 and its isoelectronic analogs, sometimes FeII and MgII UV lines). The weight of the evidence suggests that all quasars have these outflows, but they cover only a fraction of solid angle. "Line-locking" matches between features in different line profiles as well as the approximate match between the photon momentum removed in the absorption trough and the momentum in the outflow indicates that the driving force is radiation pressure. Precisely because such strong resonance line absorption is the signature of these outflows, the radiation force is most likely expressed through UV resonance lines in a manner closely analogous to the radiation-driven winds of massive stars. However, just as in that case, the technical problems standing between us and genuine understanding are formidable.

8.2.6. White dwarf cooling

More than 98% of all stars end their lives by becoming white dwarves; they can remain in that state essentially forever, slowly cooling. Detailed measurements of their spectra can then be used to infer both their mass and age, potentially providing a valuable calibrated clock for diagnosing the history of stellar populations in the Galaxy. This is, however, easier said than done. White dwarf ages are extremely sensitive to a number of poorly-understood physical issues: the equation of state of the interior; electron thermal conduction through their highly-degenerate interiors; uncertain and possibly stratified elemental abundances in their atmospheres; and inadequate atomic data for calculating atmospheric opacity. The net result of all these uncertainties has led to a situation in

which the oldest white dwarves in the Galaxy are said by some to be almost as old as the Universe (12~Gyr out of 13.7~Gyr), while others argue they were made only 8~Gyr ago.

8.2.7. X-ray pulsars

Some neutron stars have surface magnetic fields so strong ($\sim 10^{12}$ G) that they can channel accreting matter onto polar caps covering only a small part of the star's surface area. The star's rotation modulates the signal seen by distant observers into regular pulses. But these same fields are also strong enough that the electron cyclotron resonance falls in the X-ray band, making the electron scattering cross section energy- and polarization-dependent. In fact, because the energy of the cyclotron resonance is not far below $m_e c^2$, a variety of intrinsically QED effects enter. The force exerted by outgoing radiation should be great enough to decelerate the inflow, but the complexities of the radiation-matter interaction have hitherto blocked progress in understanding how this happens. The imminent advent of X-ray spectropolarimetry, potentially capable of detecting polarization-sensitive QED effects in these objects, makes this subject particularly timely.

8.2.9. Black hole accretion

Tens of percent of the total light created after the Big Bang is made by matter accreting onto black holes. Simple dynamical arguments show that in the accretion flows accounting for the great majority of this output, radiation pressure, rather than gas pressure, is the principal support against the vertical component of gravity where most of the light is made. The fact that the radiation pressure is proportional to the accretion rate when averaged over timescales long compared to the thermal-equilibration timescale implies (in linear theory) an instability in the inflow rate. Thus, we do not know the most basic fact about the most interesting accretion disks--the mass surface density profile. However, we can be sure that coupling radiation forces to disk dynamics will be essential to learning it.

A closely-related problem arises from an apparent paradox: when the accretion rate is high enough that the luminosity generated exceeds the Eddington value, radiation forces should disrupt the inflow. But the accretion rate is controlled by events far from the central gravitating object, so there's nothing to prevent this situation from arising. What happens when it does? This problem is made particularly pointed by the observational evidence suggesting that there are black holes in nearby external galaxies accreting at super-Eddington rates.

8.2.10. Neutrino transport in collapsing stars

Two of the most dramatic events that can occur in the Universe are supernovae and gamma-ray bursts. Both begin in material with near-nuclear density and both result in the release, in a time ~ 10 s, of an energy approaching the rest-mass energy of an entire star. Most of this energy is initially given to neutrinos. Although neutrinos are quite different from photons in many ways, in these cases they function in a fashion very

analogous to the way photons do in other astrophysical situations: because they are made copiously and have relatively long scattering lengths, they are the primary carriers of heat. In addition, their outward fluxes may be large enough to exert sizable forces, again in a fashion closely analogous to photon radiation forces---and they may possibly be large enough to power either a quasi-spherical explosion (in the case of core-collapse supernovae) or a powerful jet (in a gamma-ray burst).

8.2.11. Type Ia supernovae

Crucial evidence for the mystery known as “dark energy” comes from the remarkably stereotyped maximum luminosity of Type Ia supernovae. This variety of supernova is thought to arise when a white dwarf in a close binary is loaded with additional matter to the point that a catastrophic nuclear reaction is triggered. That the maximum luminosity is always approximately the same can be understood on the basis of fundamental physics: the critical mass is the maximum mass for a white dwarf, the Chandrasekhar mass; nearly its entire mass is consumed because electron degeneracy suppresses collisional energy transfer to the nuclei; and the total energy release is simply the change in nuclear binding energy due to burning C and O to Si and Ni. Decay of radioactive Ni determines the light curve.

However, this level of understanding isn't great enough to support cosmological studies at the accuracy we require. If we are to achieve distance measurements with uncertainties of 2% or less, we need to understand how small variations in the Ni/Si ratio or modest inhomogeneities in the Ni abundance can be created. Radiation hydrodynamics plays two important roles in helping to answer these questions. First, deep in the exploding matter, heat is diffused primarily by radiation transport. The magnitude of heating in advance of the propagating nuclear “flame” can have a major influence on how the reactions proceed; in addition, the rate of heat diffusion by radiation after the reactions have completed determines the heated fluid's equation of state, and therefore its dynamics. Second, when the shock fronts move out through the stellar envelope and encounter circumstellar gas, breakdowns in thermodynamic equilibrium lead to energy transport that is both non-LTE and non-local. These effects can alter both details of the light curve and also the directional dependence of the emerging light. Thus, improved understanding of radiation hydrodynamics in this context will be an important adjunct to future dark energy studies relying on Type Ia supernova light curves.

8.3. Opportunities

8.3.1. Observations

Being able to constrain the atmospheric properties of exoplanets only recently seemed to be impossible, but current space missions are already yielding results in this area. The best targets are those where the planetary systems are oriented so that they move in front of the star for part of their orbit, and vanish behind the star on the other side. For these systems Hubble Space Telescope has been able to detect absorption lines in the planetary atmospheres as the planet transits the star. Remarkably, the extraordinary precision of the

Spitzer space telescope has allowed it to detect the thermal radiation from the planet by observing in the infrared where the flux contrast between the star and planet is lower than it is in the optical. By performing these measurements as a function of wavelength and orbital phase, one can deduce much about the composition of the planetary atmosphere, because many of the main molecular absorption bands lie in the infrared. When the James Webb Space Telescope launches in 2014, a major effort will be to extend these types of studies. By then, the exoplanet database will likely include true Earth-like planets, as these are the main focus of the Kepler mission, which has just begun to produce spectacular and unexpected results. Making sense of this bewildering array of irradiated atmospheres is the province of radiation hydrodynamics.

Recent ground-based observations using adaptive optics have just begun to probe the regions of jet acceleration and the larger telescopes planned for the next decade such as the TMT and Large Magellan Telescope will further study this area. Being able to diagnose conditions within the inner parts of protostellar accretion disks where radiation plays a key role in the dynamics is a real possibility. The large millimeter telescope LMT is just coming on-line and will be able to study molecular emission within disks, another process dominated by radiation. Studies of differential motions within stellar jets are now possible using synoptic images from the Hubble Space Telescope, and these reveal much about the flow dynamics from these objects.

New wide-field infrared arrays, like the NEWFIRM camera just available at the National Observatories at Kitt Peak and Cerro Tololo, make it possible to survey entire regions of massive star formation in a short time. By observing in the light of H₂, which results from fluoresced ultraviolet irradiation, these images reveal outlines of globules that identify areas of current and future star formation. In some cases the globules show what appear to be spectacular fluid dynamical instabilities caused by the intense radiation and winds from the nearby massive stars. As in the other cases described above, radiation hydrodynamics is dominating the physics of these objects.

The province of radiation hydrodynamics also extends to the relativistic regime in the most exotic of objects, gamma ray bursters. The Swift satellite has been operational for a few years now and regularly discovers gamma ray bursts that are now routinely followed up by observatories on the ground and in space. A major effort of the newly-launched Fermi gamma ray telescope is to measure how the overall spectral energy distribution of the bursts evolves with time. Models of this phenomenon rely entirely on how radiation transfers within the burst. As in the above cases, interpreting the results from these missions goes hand in hand with the study of radiation hydrodynamics.

8.3.2. *Experiments*

Some problems, however, display the fortunate coincidence alluded to in the introduction: an approximate match between conditions we can create in the laboratory and those prevailing in the astrophysical objects. With the high energy density (HED) facilities now operating worldwide, such as high power lasers and magnetic pinch facilities, densities, temperatures, and radiation temperatures in the range of $n_e = 10^{17} -$

10^{25} cm^{-3} , $T_e = 1 \text{ eV} - 10 \text{ keV}$, $T_r = 10 - 400 \text{ eV}$, can potentially be accessed. Plasmas may now be produced with tailored elemental compositions, with 0.01-10 cm spatial scales and 0.1-100 ns timescales, and “tunable” to make density and temperature (spatial, temporal) gradient scale lengths shorter or longer than the plasma (size, duration). X-radiation with thermal, power-law and/or NLTE/line-emission characteristics can be made. Hence, there are many other examples of astrophysics research that could benefit from laboratory experiments.

We now list a few examples where laboratory astrophysics experiments seem particularly fertile for development. (1) Experimental conditions can be created that reproduce those in stellar interiors, allowing measurements of complex opacities to be made. These opacities are central to stellar evolution models, and the dynamics of stellar interiors. For example, an improved knowledge of the opacity of Fe at high density and temperature is required to resolve uncertainties in the location of the radiative zone in the sun. (2) One of the difficulties in constructing good atmosphere models for white dwarfs is to describe appropriately the degree of line-broadening that occurs in such high densities. These may be possible to create, however, in the laboratory in laser- or Z-pinch-heated plasmas, where densities of 10^{17} cm^{-3} at temperatures of $\sim 1 \text{ eV}$ may be in reach. Models of white dwarf equations of state could become experimentally testable when plasmas with densities in the range 10^{24} - 10^{26} cm^{-3} and temperatures $\sim 100 \text{ eV}$ can be created. (3) Radiation flow through an expanding atmosphere with a large number of atomic resonance lines is a difficult theoretical problem central to understanding stellar winds from massive stars. Add in large velocity gradients from exploding systems, such as occurs in calculating supernova light curves, and this problem becomes even more challenging. Scaled experimental tests of both scenarios are possible, and would improve our understanding of massive stars and supernovae. (4) One of the most inspiring examples of radiative hydrodynamics in the sky is the majestic columns in the Eagle Nebula. Here, intense UV radiation from a few bright young stars drives deep nonlinear radiative-hydrodynamics through the pressure created via photoevaporation at the molecular cloud surface. Simulations of these nonlinear radiation hydrodynamics are notoriously difficult, yet essential, if we are to understand the dynamics of star forming regions. Well scaled experiments could be invaluable here to test such simulations. (5) Radiative shocks occur in many situations in astrophysics, such as supernova remnants (SNRs), protostellar jets, and shocks propagating through molecular clouds. Radiative shock instabilities are thought to contribute to the crenulated structures seen in many SNRs. Radiative cooling in shocked clumps in molecular clouds may be a trigger for star formation, and be a key ingredient in star-burst activity. Yet simulations of such radiative effects are difficult, and in most cases, untested with experimental data. Capabilities now exist for such experimental tests. (6) Accreting compact objects, such as black holes and neutron stars, are some of the most fascinating objects in the universe. Much of our understanding of their accretion dynamics comes from observations of the photoionized plasmas in their extended accretion disks. Modeling of these accretion dynamics requires good understanding of photoionized plasmas in the presence of intense fluxes of radiation. Uncertainties in our understanding of these dynamics could be reduced by scaled laboratory experiments, which are now possible. (7) The destruction or processing of interstellar dust grains by the intense fluxes of x-rays and UV radiation from gamma

ray bursts (GRBs) has a significant affect on our interpretation of GRB light curves and afterglow. Yet the theoretical uncertainties in our understanding of this dust destruction are very large. Experiments here are also likely possible, and would be very beneficial in improving our understanding of GRBs.

8.3.3. Theory and Simulations

In most of the cases described above, the greatest opportunity for progress lies in more powerful computational tools, ultimately checked by comparison with observations and, where possible, laboratory experiments. Both algorithms and hardware have been developing rapidly in recent years, leading both to some signal achievements and to hope for much more to come in the near future. The chief issue in advancing numerical radiation hydrodynamics is the creation of radiation transfer algorithms both accurate enough to capture the physics and rapid enough to be employed in concert with hydrodynamic or magneto-hydrodynamic simulation codes. Hitherto most work has relied upon the flux-limited diffusion approximation, which provides a good description when the optical depth is large, but can fail dramatically when the scattering length becomes comparable to or longer than other relevant length scales and the geometry is more than one-dimensional. Improved methods of a variety of natures (using the method of short characteristics, or Monte Carlo sampling, for example) are, however, already visible on the horizon. Coupled with the continuing rapid growth in the sizes of computer clusters and the even more rapid fall in the price of disk storage, significant advances in the next few years are very likely.

8.4. Impact and Major Outcomes

The potential for major impact, both in astrophysics and laboratory physics, comes from the linking of astronomical observations, theory, simulations, and experimental verification and validation. The use of experiments will lead to improvements in the theories and simulations, which in turn, will motivation new observations, closing this research loop. Astrophysics and astronomy has never had an experimental V&V component strongly coupled to their routine research. Conversely, through a strong coupling to astronomical observations plus theoretical interpretation, laboratory experiments will gain important insights into plasma physics at the most extreme conditions. This new approach to plasma astrophysics and laboratory plasma physics will lead to improved understanding in aspects of many, if not all, of these astrophysical phenomena: exoplanets, star formation, solar structure and composition, radiation from massive stars, radiation in relativistic astrophysics, white dwarf cooling, x-ray pulsars, black hole accretion, neutrino transport in collapsing stars, and Type Ia supernovae.

8.5. Links to Other Topics

There are links of radiation hydrodynamics to many, possibly all of the other topics: magnetic reconnection, shocks in astrophysics, waves and turbulence, magnetic dynamo, interface and shear instabilities, momentum transport, dusty plasmas, relativistic plasmas, and jets and outflows.