8. Radiation Hydrodynamics in Astrophysics

8.1. Introduction and Current Status

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 radiation 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 conditions.

Even though astrophysical systems can be quite different from terrestrial ones, there are genuine similarities to laboratory plasmas. In radiation-driven inertial confinement fusion systems, for example, 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 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. Key Scientific Challenges

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

8.2.1. How are the largest stars formed?

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 and x-ray radiation. Irradiation may tilt the size distribution of interstellar dust, changing its total opacity. There are now stunning examples of accretion disks around forming stars photoevaporated by the young massive stars in their proximity. Another example is the majestic pillar structures in molecular clouds that are driven by photoevaporation from young massive stars just turning on in star forming regions. (Fig. 1a.) 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 these disks do not extend all the way to the star, but are truncated at some radius, probably at the point where radiation from the star sublimates the dust in the disk. Radiation also plays a key role in determining how disks transfer angular momentum outward. 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 a 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 issue that occurs throughout astrophysics in young stars, X-ray binaries, active galactic nuclei, and possibly even planetary nebulae. The associated radiation transfer problem is both multi-dimensional and frequency-dependent, and 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 together.

The Sun continues to provide new challenges for stellar physics. Helioseismology is the most powerful tool used in studies of the Solar interior; it enables precise tests of how accurately Solar models predict the Solar structure and, in particular, how well they predict the interior radiation transport. 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? Stellar interior models require input about properties of stellar matter such as opacities, and those material property models can now, for the first time be experimentally measured at relevant conditions. The combination of precision observations, detailed models, and new ability to measure the properties of stellar interior matter in laboratories provide an opportunity to answer these questions. The results will refine our picture for the internal structure and chemical composition of the Sun and most other stars.

8.2.2. How do stars explode as supernovae?

The explosions of massive stars occur by the collapse of their cores (Fig. 1b.), but several distinct types of core-collapse supernovae are thought to exit. Although Type II supernovae (collapse of a massive star that has retained its hydrogen-rich envelope) are the most common, much recent attention has been given to the speculation that still more energetic explosions, called "hypernovae", may be the sites of (some) gamma-ray bursts. All supernovae are strongly radiation hydrodynamic events, with the radiation pressure exceeding the material pressure for long periods. The details of the explosion mechanisms are far from well understood. It may be that the early neutrino heat transport, which is strongly convective, combined with later dynamics during the explosion, are sufficient to explain the observed distribution of ejected material. Alternatively, mechanisms involving rapid rotation and strong magnetic fields in the stellar core may conspire to produce jet-driven explosions. Astronomers are now beginning to obtain observations of the emergence of the shocks from these stars as they explode. There is also the possibility that core-collapse explosions in red supergiant stars can create a sufficiently strong radiative shock that it affects the hydrodynamic mixing in the envelope. The models applied to this problem have had limited physical fidelity and no demonstration tests based on experiments. At much later times, when the ejected material has expanded into the interstellar medium, supernova remnants go through a phase in which radiative heat losses from the strong shock launched by the explosion significantly affects the evolving dynamics. (Fig. 1b.) When the stellar remnant left behind is a highly-magnetized neutron star, such as the Crab Nebula, relativistically strong electromagnetic waves coupled to the plasma can energize the entire remnant in spectacular fashion.

Type Ia Supernovae (SNe-1a) originate from thermonuclear explosions of White Dwarf stars (WD) whose mass has grown to exceed the limiting Chandrasekhar mass. When the WD approaches the critical mass, a nuclear burning front is triggered which then consumes the WD. The maximum luminosity can vary by up to a factor of ~10. There exists a universal relation, however, between the absolute brightness and the width of the light curve, which allows SNe-1a to serve as very bright, standardized candles. This property led to the discovery of dark energy. Planned dark energy studies will need calibration of SNe-Ia luminosities at the 2-3% level. This requires a much improved ability to model SNe-1a light curves. Radiation hydrodynamics plays two important roles. First, deep in the exploding matter, heat is diffused primarily by radiation transport. The magnitude of heating in advance of the propagating nuclear "flame" (ie, radiative preheat) can have a major influence on how the reactions and dynamics proceed. Second, when the shocks move out through the stellar envelope into the circumstellar gas, breakdowns in thermodynamic equilibrium lead to energy transport that is both non-LTE and non-local. These effects can significantly alter the details of the light curve. Improved understanding of radiation hydrodynamics will be an important adjunct to future dark energy studies relying on SN-Ia light curves.

8.2.3. How do black holes radiate?

Tens of percent of the total light created after the Big Bang was made by matter accreting onto black holes. (Fig. 1c.) 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; in other words, our standard picture of accretion disk equilibrium may not describe real disks in Nature. In fact, even in those regions where gas pressure is greater than radiation pressure, current computational techniques are inadequate to define the heating-cooling balance that determines the fluid equation of state.

A still more serious paradox emerges when the accretion rate is high enough that the luminosity generated exceeds the Eddington value. In such a state, 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. Understanding how radiation couples to the disk dynamics will be essential to making progress in this area.

Yet another another example of radiation hydrodynamics in accreting black holes is found in the spectra of quasars. These objects are thought to be actively accreting supermassive black holes, $\sim 10^8$-10^9 solar masses, each at the center of a galaxy. In ~15% of the population, very broad absorption troughs (~10,000 km/s) are seen to the blue of the systemic redshift in a number of ionic resonance lines. All quasars likely 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.

8.2.4. How does intense stellar radiation affect exoplanet atmospheres?

Only one decade since radial velocity surveys uncovered the first planets around other stars, the number of such planets has soared to over 400, and the numbers keep rising (Fig. 1d.) . 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 planetary 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 scenario that includes Jupiter-sized planets orbiting 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. Exactly how such intense radiation will affect these exoplanet atmospheres is only now starting to be thought about.

8.3. Major Opportunities

Many of the opportunities in this field are the result of improvements in either computational power or experimental facilities. Combining the two, in the form of testing simulation codes on idealized problems realizable in the laboratory, promises to be exceptionally fruitful. After this sort of code validation and verification (V&V), we can gain greater confidence in the results of these simulation codes when they are applied in contexts closer to the actual astrophysical situations.

8.3.1. Opportunities for understanding star formation.

Understanding how stars are formed, and the nature of their interior structure has been one of astronomy's most enduring problems. The star formation problem encompasses a vast range of scales and conditions. The collapsing gas sheds its angular momentum in a complex interaction with magnetic fields, possibly aided by the ejection of protostellar jets. When the new star starts to burn, it radiatively drives the surrounding molecular cloud, possibly triggering additional star birth.

Modeling of these dynamics requires 3D radiation-MHD simulations with radiation, electrons, ions, neutrals, dust, magnetic fields, turbulence, and nuclear burning. The rapid advance of computational power offers great opportunities for progress in this area. More powerful algorithms, ultimately checked by comparison with observations and, where possible, laboratory experiments can soon be brought to bear. 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. Improved methods of a variety of natures are already visible on the horizon.

Experimental conditions can be created for the first time that reproduce those in stellar interiors, allowing measurements of complex opacities to be made. These opacities are central to stellar birth, stellar evolution, and the detailed dynamics of stellar interiors. One of the most inspiring and widely recognized 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 from 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 would be invaluable here to test such simulations. Radiative shocks occur in a number of phases of star formation, such as in the ejected protostellar jets, and in shocks propagating through molecular clouds. Radiative cooling in shocked clumps in molecular clouds may, in fact, be a trigger for further star formation. Simulations of such radiative effects, however, are difficult, and in most cases, are as yet untested with experimental data. Facilities now coming on line, however, offer the potential of testing these codes in conditions scaled to the astrophysical context. Dust contributes in a major way to the star formation process. In molecular clouds, it radiates away excess thermal energy, keeping the cloud cold and dense. The interaction of the dust with these strong radiative shocks in the cloud is a major unknown in the dynamics of star formation. Experiments to test our understanding of shock and/or radiation processing of dust seem possible on current facilities.

Recent ground-based observations using adaptive optics have just begun to probe the regions of protostellar jet acceleration, and the larger telescopes planned for the next decade, such as the Thirty Meter Telescope (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 (HST), 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 from H_2, 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. Additional telescopes that will be highly valuable in this area are James Webb Space Telescope (JWST); Stratospheric Observatory for Infrared Astronomy (SOFIA); and the Atacama Large Millimeter/submillimeter Array (ALMA).

8.3.2. Opportunities for understanding supernovae.

Understanding supernovae, both core-collapse and thermonuclear, is a grand challenge of the highest degree. Modeling supernova explosions in their entirety will require 3D simulations that include gravity, nuclear EOS, nuclear reaction chains, nuclear burn wave evolution, intense neutrino fluxes, radiation, magnetic fields, turbulence, and (for the light curve) non-LTE, non-local radiation transport. Experiments can contribute in several ways. Laboratory conditions can be matched to those of stellar interiors to provide test-beds for measuring atomic opacities. Nuclear reaction rates can also be measured. Beyond this, 3D radiation transport codes can be tested by matching their boundary conditions and parameters to those achievable in the lab.

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. The even larger velocity gradients of supernova explosions make this problem still more challenging. Scaled experimental tests of both scenarios may be possible, and would improve our understanding of massive stars and supernovae. Radiative shocks occur in core-collapse supernovae and supernova remnants (SNRs). Radiative shock instabilities are thought to contribute to the crennelated structures seen in many SNRs. Yet simulations of such radiative effects are difficult, and in most cases, untested with experimental data. The destruction 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. 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 and interpretation of GRB light curves and afterglow.

Observationally, 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. The SuperNova Acceleration Probe (SNAP) satellite is a proposed space observatory designed to measure the expansion of the Universe, by observing Type-1A supernovae. The Joint Dark Energy Mission (JDEM) will be jointly funded and developed by NASA and the Office of High Energy Physics at the U.S. Department of Energy (DOE). Its mission will make precise measurements of the expansion rate of the universe to understand how this rate has changed with time.

8.3.3. Opportunities for understanding accreting black holes.

Black holes are some of the most fascinating objects in the universe. (Fig. 1c.), but modeling their surrounding flows will require 3D simulations that include intense radiation, strong gravity, magnetic fields, turbulence, and strong radiation forces. At the moment, the state of the art in global accretion modeling includes 3D MHD turbulence in full general relativity, but does not incorporate either a realistic equation of state or radiation forces. However, researchers in the field are poised to add these elements as they develop new algorithms and can run their codes on ever-faster computers. Many of the same techniques developed for radiation/MHD simulations in the star-formation context can be readily applied to the black hole accretion problem as well. Similarly, the same experimental tests of code components applicable to the star-formation problem will likewise benefit these codes. A key observational diagnostic of accretion flows comes from the profile of the Fe Kα emission line, whose emissivity is sensitive to the ionization balance in the accretion disk atmosphere. New laboratory experiments have the potential to improve our knowledge of key atomic data (photoionization cross sections and fluorescence yields) necessary for appropriate interpretation of these emission line data.

Observations will play a key role in developing an understanding of the dynamics of accreting black holes. Currently-operating telescopes relevant to this area include the Chandra and XMM-Newton X-ray Observatories; several new telescopes, such as NuStar and the very first astronomical X-ray spectropolarimeter, GEMS, are planned for launch in the next several years; the

International X-ray Observatory may be launched some time in the future.

8.3.4. Opportunities for understanding exoplanet atmospheres.

There are enormous challenges to predicting, measuring, and understanding the nature of exoplanet atmospheres. Making predictions of explanet atmospheres requires very large scale computer simulations using 3D radiation-MHD codes which include electrons, ions, radiation, neutrals, dust, and the couplings between them. These exoplanet atmosphere models will need to be guided by astronomical observations with next generation telescopes and satellites that under construction, being planned, and soon to be launched. Code simulations of such sophistication will require extensive verification and validation (V&V) tests with experimental data. In particular, input data such as UV opacities, radiation-plasma-dust interaction rates, and possibly equation of state (EOS) will be required. Suitable experimental techniques will need to be developed for this purpose. Dust could play a major role in the astronomical observables from exoplanet atmospheres. In particular, the intense radiation from the parent star will interact dynamically with the dust in the atmospheres to drive the chemistry, climate, and observational signatures. Experiments in this area could be started in the near future, yet little to no work has been done in this area to date.

Determining 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 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 (JWST) launches in 2014, a major effort will be to extend these types of studies. The JWST will be an orbiting infrared observatory that will complement and extend the discoveries of the Hubble Space Telescope, with longer wavelength coverage and greatly improved sensitivity. The longer wavelengths enable the JWST to look much closer to the beginning of time and to hunt for the unobserved formation of the first galaxies, as well as to look inside dust clouds where stars and planetary systems are forming today. 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. This mission is specifically designed to survey our region of the Milky Way galaxy to discover hundreds of Earth-size and smaller planets in or near the habitable zone and determine how many of the billions of stars in our galaxy have such planets.

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 motivate 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.

8.5. Connections 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.

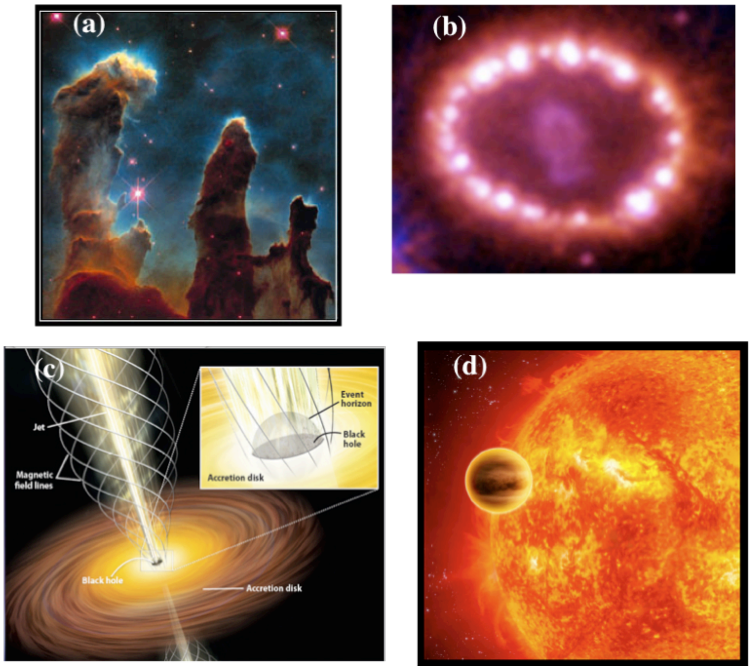

Figure 1. Images showing areas of plasma astrophysics where radiation hydrodynamics plays a dominant role: (a) the stellar “nursery” known as the Eagle Nebula; (b) remnant from SN1987A; (c) artist’s concept of an accreting black hole. (d) artist’s concept of an orbiting exoplanet in close proximity to its parent star.