Current Issues

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Abstract. Cosmic explosions are observed in many astrophysical environments. They range in scale from hydromagnetic instabilities in the terrestrial magnetotail and solar "nanoflares" to cosmological gamma ray bursts, supernovae and the protracted intervals of nuclear activity that produce the giant quasars. There are many parallels in the analysis of the explosion sites that are highlighted at this workshop, specifically stellar coronae, accretion disks, supernovae and compact objects. In this introductory talk, some general issues are discussed and some more specific questions relating to the individual sites are raised.

INTRODUCTION

A star lives its life, from the time that it is born out of a loose assembly of molecular gas till it makes its quietus as a white dwarf, neutron star or black hole, fighting gravity. Although it eventually looses the fight (unless it manages to make a Type Ia supernova), it does not concede gracefully. Time and again it finds itself transitioning from a metastable equilibium to a state of lower energy on a dynamical timescale. Similar principles govern the evolution of galaxies where there can be runaway formation of massive stars or episodic accretion onto the central, massive black hole. These are "Cosmic Explosions" - the topic of this workshop. When I was first asked to introduce "Current Issues", I thought the title curiously apposite because it is ultimately currents - electrical, weak (charged and neutral) and (with some license) strong - that are responsible for these impulsive releases of energy. Out of the many astrophysical sites that could have been included on the program, the organizers have chosen to concentrate on a few of the most interesting ones, that I shall consider in turn - the solar corona, accretion disks surrounding young stellar objects, novae, supernovae, "hypernovae" and jets. As I am neither competent nor patient enough to describe these in any detail, I have chosen to list some recent advances in our observational and theoretical understanding in each case and to pose a few questions some of which may already have answers which I hope subsequent speakers will provide. In view of the large range of topics reviewed I cannot hope to give a representative or even useful bibliography, and so I shall

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give none and defer to subsequent speakers.

SOLAR AND STELLAR FLARES

The combined observations of the YOHKOH, SOHO and TRACE satellites are transforming our view of the solar corona and, consequently, of the surface activity of other stars. In particular they have given us an appreciation of the dynamics of magnetic field lines as they are gently shuffled by underlying convective motions. The whole region above the photosphere is permeated by a *magnetic carpet* which is re-woven every couple of days. The solar prominences and coronal arches, prominent in X-ray images are just the regions where the plasma happens to be hottest and, contrary to what might have been thought, the magnetic field is *weakest*. This magnetic activity is intrinsically dissipative and this keeps the corona at million degree temperatures and launches the solar wind.

The quiet solar wind appears to be a simple and quasi-steady flow at least at high latititude (as measured by the Ulysses spacecraft) with poloidal and toroidal magnetic field components declining as $\propto r^{-2}, r^{-1}$, respectively. By contrast, the equatorial outflow appears to be dominated by unsteady coronal mass ejections. The equatorial current sheet is naturally unstable and develops its characteristic "ballerina skirt" sector structure. (Perhaps something similar has been observed by Chandra in the Crab Nebula.) Solar physics has much to teach us about accretion disks, where the underlying motions are much faster and, necessarily, supersonic. It should be no surprize that they are often accompanied by hot coronae, that dissipate a large fraction of the gravitational energy release, and powerful outflows.

My list of questions includes:

- What are the true laws of astrophysical MHD? Traditional, global MHD has been based upon analytic solutions of the equations of conservation of mass, momentum and flux under conditions of high symmetry ignoring dissipation. However, real MHD is heavily influenced by the microphysical behavior of current sheets, tiny reconnecting regions, shock fronts etc in much the same way that hydrodynamic flows are beholden to boundary layers. Perhaps there are simple, phenomenological rules which can reconcile these two approaches.

TABLE 1. Observed Characteristics of Some Cosmic Explosions

Explosion	Energy (erg)	Timescale (s)	Power (erg s^{-1})
Solar Flares	10^{32}	10^{4}	10^{28}
FUORs	10^{45}	10^{9}	10^{36}
Novae	10^{44}	10^{6}	10^{38}
Supernovae	10^{50}	10^{6}	10^{44}
Hypernovae (GRBs)	10^{53}	10^{2}	10^{51}
Jets	10^{61}	10^{14}	10^{47}

- What is a solar flare? We know of many examples of magnetostatic configurations that can be slowly altered until they become unstable and release a large amount of magnetic energy. However we do not understand which of these are most likely to occur in practice and what is the partition of the release of energy between local heating and the bulk kinetic energy that drives outgoing shock waves. (Similar questions exist in earthquake studies.)

- What is the structure of shock fronts? Simulation and *in situ* measurement has greatly improved our understanding of collisionless shocks. It appears that thermal electrons are commonly transmitted with sub-equipartition energies, as is also found to be the case with supernova shock waves. The detailed plasma physics still eludes us, though. This issue is related to the question of the injection of suprathermal ions into the first order Fermi acceleration process that appears to be responsible for producing most Galactic cosmic rays.

- What determines the energy and length scales that dominate coronal heating? The form of this dissipation appears to be primarily reconnection and to be dominated by frequent "nanoflares", (although this conclusion is still controversial). This realization has, in turn, stimulated analysis of new modes of magnetic reconnection. Still, it is the occasional giant flare that commands our observational attention and provides the most detailed diagnostics.

- How is the solar wind launched? The observed coronal temperature is insufficient to give the gas its 700-800 km s^{-1} outflow speed as measured by Ulysses. This leaves hydromagnetic wave acceleration as the prime suspect. Understanding the acceleration and stability of the solar wind is highly relevant to the study of jets.

YOUNG STELLAR OBJECTS

Accretion disks and bipolar outflows appear to be a standard feature of star formation. The optical jets can propagate through the interstellar medium over distances more than $\sim$ 10 pc, quickly polluting it with magnetic field and metals (an observation of some cosmological importance). However, this outflow is not steady. In particular, thermal instability of the accretion disk produces "FU Ori" outbursts where perhaps $\sim 0.01\ M_\odot$ of gas are expelled with comparatively high speed over a decade or so every ten thousand years. Smaller scale explosions create the "Herbig-Haro" objects which are presumably traveling forward-reverse shocks. These are sometimes observed in matched pairs, one in each jet confirming that they originate at the disk. The morphological similarity to, for example, the knots in the M87 jet is clear.

Some important questions include:

- How much of the mass in the original protostellar disk accretes onto the central protostar and how much is lost in the form of a wind or jet? A related question is how much of the angular momentum is removed in this manner as opposed to being transported radially in the disk to large radii where it can, supposedly be extracted by large tidal torques.
- How much mass and energy is associated with the FUOR outbursts and how much is transported in the long intervals between outbursts? (It is not clear how far one can push the dynamical analogy but similar questions have been raised in trying to understand the Galactic microquasar GRS 1915+105.)
- How are the optical jets collimated and confined? Magnetic collimation is commonly invoked, but even here, several alternatives have been discussed. The field may be primarily vertical near the disk and shape the outflow through magnetic pressure. Alternatively, the field may have a significant radial component so that the jet can be launched centrifugally so that the hoop stress associated with toroidal field may be largely responsible for the collimation. A third possiblity, that has been discussed, is that the magnetic field be mostly toroidal near the disk and wound up like a coiled spring so that it can push the gas away vertically. Observations of protostellar outflows have as good a chance as those of any jets of measuring the magnetic structure. Ultimately the flow must be confined laterally at large cylindrical radius. It is not clear whether this is achieved by the ram pressure of infalling gas or through the application of a quasi-static thermal pressure.
- What is the dynamical structure of Herbig-Haro objects and what can they tell us about the explosions that cause them? Forward-reverse shocks arise naturally if the velocity with which the jet is launched varies so that the faster moving gas overtakes the slower outflow and forms a shock. The pressure behind this shock front may be sufficient to form a reverse shock giving a characteristic dynamical structure. The high pressure inter-shock gas will expand transversely, weakening the shock strengths. Again, observations should help us to understand what is really happening.

NOVAE

Classical novae, by contrast, are thermonuclear explosions which arise when hydrogen-rich gas from a companion accumulates on the surface of a C-O or O-Ne-Mg white dwarf and then detonates, initially uncontrollably, under degenerate conditions. The energy release per nucleon is enough to heat the gas above the Fermi temperature, causing it to expand, and then above the escape energy. As several of the nuclear reactions involve weak interactions that take place on timescales that are long compared with the dynamical timescales, the ejected gas is believed to contain many prominent radioactive species that can act as monitors of stellar activity.

X-ray novae involve similar processes occuring on the surface of a neutron star. Here, the reactions occur much faster but the gravitational potential well is so deep that the gas cannot escape using its own thermal pressure. (It may be expelled by radiation pressure, however.) Naturally, this burning will not occur uniformly over the surface of the star and rotational modulation of the X-ray emission was predicted and is observed. (Curiously, the rotational frequency is observed to vary slightly, which may be due to elevation of the X-ray photosphere by radiation pressure with approximate conservation of angular momentum.

My personal question list for novae is:

- What can be learned by observing radioactive nuclei and positron annihilation from classical novae? Novae are prime targets for missions like INTEGRAL and HESSI that promise to open up the new field of MeV spectroscopy. We need to go beyond mere detection of radioactive nuclei and use measurements of line strengths and widths to learn about the underlying explosion.

- What is the status of the beat-frequency model of QPOs? This posited that the neutron star was rotating with a period similar to that of the inner regions of the accretion disk and that the observed, varying frequencies were a beat rather than a fundamental. The first part of this hypothesis has been vindicated, but I wonder about the evidence for the second part?

- Are *any* QPO modes due to neutron star osciallations? The problem here is that some of the modes that had been attributed to neutron star oscillations are also found in black hole systems. (Neutron star modes can only provide the clock because the energies associated with them are necessarily quite small.)

- Can we measure the neutron star mass-radius relation? One of the best ways for high energy astrophysics to repay its immense debt to nuclear physics is to measure the equation of state of cold nuclear matter (in contrast to the hot nuclear matter that will be explored by heavy ion colliders). This may be possible through measuring the gravitational redshift of atomic and nuclear lines from the surface of hot neutron stars, however it is not clear what it will take to do this in practice.

SUPERNOVAE

Supernovae are once again at center stage. In cosmology, Type Ia explosions have been modeled empirically as one parameter standard candles, and if this is the case, they suggest that the universe is entering a (second?) epoch of inflationary expansion. This is a remarkable discovery, if true. In addition, there is circumstantial evidence that at least some types of γ-ray bursts are associated with supernovae, both through the suggested identification of GRBs with star forming regi ons and the possible discovery of supernova light curves in a few instances. For both lines of research to advance, it is imperative to develop a far better understanding of the physics and the astrophysics of supernova explosions.

The blast waves that result from these explosions are not always well-described by Sedov point explosions in uniform media. Even if the energy release is fairly isotropic (and there are several reasons for suspecting that it is not) the external medium is likely to be anisotropic. The beautiful images of η Car and SN 1987a, the former being an accident waiting to happen and the latter being one that we are still witnessing, explain why so many mature supernova remnants are quite non-circular despite having essentially isobaric interiors. These supernova remnants are excellent laboratories for studying particle acceleration and magnetic field amplification at shock fronts that provide a bridge between heliospheric studies and more energetic phenomena associated with AGN and GRBs. Non-relativistic shocks behave quite differently from relativistic shocks and so it is fortunate that we have plerions like the Crab Nebula and classic remnants like Tycho so close to home to study.

The questions:

- How important are Type Ia supernova evolutionary corrections? The big concern, as always with cosmographic studies of the expansion of the universe, is whether or not we are confusing kinematics with physical evolution. This is particularly troubling here because there is no commonly agreed identity for the progenitors of these explosions and, I believe, no consensus yet on the reason for the "Phillips" correction although some promising suggestions have been made. There are internal consistency checks and some of these have already been satisfied but more will be needed before we can sign off on the result.

- How do we classify supernovae observationally? I doubt that I am alone in not understanding the spectroscopic and physical distinctions between the various types of supernova Type Ibc, Type IIn etc. I hope we can have a primer on the subject here.

- What are Type Ia supernovae anyway? Single degenerate and double degenerate models have their advocates. Likewise for detonation of Chandrasekhar mass CO white dwarf versus an off center explosion in a lighter star with a helium envelope.

- When do Type II supernovae form black holes as opposed to neutron stars and what are the associate d rates? This question is timely because Chandra has just discovered a point source inside Cas A, and as of now, the odds are about evens for it being a black hole or a neutron star.

HYPERNOVAE

Gamma ray bursts continue to amaze. There has been direct verification that the long duration bursts are located at cosmological distances through the measurement of redshifts. (The same is probably true for the short duration bursts, although HETE2 is probably going to be necessary to verify this.) This leads to an impressively broad range of isotropic burst energies, from $\sim 10^{-6}$ $M_\odot c^2$ in the case of GRB 980425 to ~ 2 $M_\odot c^2$ for GRB 990123 - hardly standard candles (though this has not prevented some from trying to use them for cosmography). GRBs are now widely interpreted as optically thick fireballs created with large entropies per baryon, like the universe itself. The actual γ-ray emission, lasting for up to a few minutes, is commonly thought to be produced by internal shocks in the expanding ejecta and this accounts for the great heterogeneity in observed γ-ray burst time profiles. The ninth magnitude optical burst, seen by ROTSE from GRB 990123 (with an isotropic energy $\sim 10^{-3}$ of the total) may be caused by a reverse shock. Studying the afterglows is proving to be interesting in its own right, for what it has to say about the behavior of relativistic shocks, as a probe of the environment in which the burst occurs, as a measure of the explosion energy and as an indicator of beaming. Broken power law spectra are observed and these have been variously interpreted as being due to cut-offs in the electron distribution function, radiative cooling and self-absorption.

A recent development is the circumstantial evidence for the association of GRBs 970228, 980326, 980425 with supernovae, albeit of different types. If the association is also with young stars, then GRBs will be invaluable probes of the early universe and galaxy formation. Another somewhat more secure story is that soft γ-ray repeaters are "magnetars". That is to say, their outbursts are magnetically powered and originate on the surfaces of young neutron stars with surface magnetic fields $B \gtrsim 10^{14}$ G.

It is hard to limit the number of questions in this subject.

- Are GRBs beamed? In my view, although the jet hypothesis is eminently reasonable and fits in with some source models, especially collapsars, we are really only interpreting occasional steepening in the light curves in this manner, rather than seeing the clear evidence that was provided by VLBI in the case of AGN. The argument that the bursts must be beamed, otherwise they would have energies in excess of a stellar rest mass, reminds me of a similar argument in favor of them being local!

- Are there γ-ray quiet afterglows? These are surely a prediction of beaming. At present the observational constraints are surprisingly poor.

- Is magnetic field amplified at external shocks? We know from observations of young supernova remnants that relativistic protons and electrons are accelerated at non-relativistic shock fronts and that thermal electrons are transmitted with temperatures below the equipartition value. However, in a source like Cas A, it appears that the magnetic field only becomes strong in the interaction zone between the shocked interstellar medium and the explosion debris. (It is noteworthy that even as impressive a radio source as Cas A is four orders of magnitude under-luminous relative to a homogenous, maximally emitting synchrotron source with the same total pressure.) What is assumed makes a big difference. When Chris McKee and I computed the nonthermal emission that would be observed from decelarating, relativistic blast waves, we assumed that the magnetic field is just compressed along with the gas in passing through the relativistic shock front. In this case, $\epsilon_{\rm mag}$, the ratio of the magnetic to total energy density is only $2v_A^2/c^2 \sim 10^{-9}$ in the interstellar medium, where v_A is the Alfvén speed ahead of the shock front. More recent calculations, that are applied specifically to GRB afterglows, generally assume that $\epsilon_{\rm mag} \sim 10^{-2}$ which is necessary to fit the fluxes (although the scaling laws are unchanged). For this reason and because the best studied GRB afterglow, GRB 970508, shows no sign of a mildly relativistic transition in the particle acceleration efficiency, I still suspect that the afterglow emission originates well downstream from the outer shock.

- Are GRBs really associated with supernovae? The late time light curve seen in GRB 980326 could have a different explanation. In particular, as Ann Esin and I have been considering, it fits rather well with scatttering of the initial optical burst by dust just outside the sublimation radius. This occurs typically at a distance $\sim 10^{18}$ cm. As refractory dust has high albedo and is forward scattering, the characteristic delay is plausibly a few months, as observed.
- How easy is it to have an ultrarelativistic jet emerge from inside a collapsing star? Entrainment of gas might easily occur and prevent the flow from attaining bulk Lorentz factors ~ 300.
- Are the "cyclotron" lines real and the ~ 300 keV "breaks" generic and, if so, can they be formed in ultrarelativistic outflows? Existing explanations seem a little contrived.
- What is the underlying physical mechanism for creating the fireball? Most models now seem to involve black holes, magnetic field and wishful thinking. The problem is hard. T he main challenge is to amplify the magnetic field fast enough to make an electromagnetic bomb. Fortunately there are new ingredients in the strongly curved spacetime around a black hole or a pair of orbiting neutron stars. The orbits can precess differentially at near relativistic speed and this can lead to an extremely rapid field growth - faster than conventional dynamos and, indeed, faster than exponential. This, in turn, induces $\gtrsim 10^{22}$ V EMFs which cannot be shorted out and accelerate pairs directly.

JETS

The black hole model of AGN has been vindicated observationally, and, beyond all reasonable doubt, most normal galaxies, like our own contain central black holes with masses in the million to billion solar mass range. There are also at least nine well measured compact object masses in excess of $\sim 2.5\ {\rm M}_\odot$ that are surely also black holes. There are promising, but so far less compelling indications that some of these holes spin rapidly.

Jet are a common, though not universal, accompaniment of accretion which suggests that they are involved in carrying off some of the energy and angular momentum released by the infalling gas. However, we do not understand how they are formed or even if there is a universal mechanism at work. We do know that magnetic field must grow to dynamically significant levels in accretion disks and most jet formation models now involve magnetic field except perhaps when the mass accretion rate greatly exceeds the Eddington rate. Our understanding of the emission from jets has also advanced. The discovery of rapidly variable GeV and TeV γ-rays from blazars shows that they can be extremely luminous. Radio astronomers have been mapping the smoke not the fire. The standard radio synchrotron model is also under assault. There is increasing evidence that compact components have brightness temperatures well in excess of the inverse Compton limit, even allowing for plausible Lorentz factors. Large degrees of circular polarization are also being reported. All of this suggests that some alternative, possibly coherent emission mechanism is at work at least in the compact cores. (Note, that it is not sufficient to explain how high brightness radio emission is *emitted*. It is also necessary to explain how it is *transmitted* out of the nucleus when there are many potential non-linear scattering mechanisms which will degrade the brightness temperature.)

In an impressive display of the power of VLBI, the radio astronomers have been able to show that the M87 jet is collimated within $\sim 100m$. If relativistic jets are powered by the black hole itself or the gas flow around the black hole then their energy has to be carried *initially* in some form other than electron-positron pairs, which are subject to catastrophic radiative losses. Electromagnetic Poynting flux is the prime suspect. In other words, relativistic jets are starting to resemble pulsars. (Contrariwise, the Crab pulsar now appears to form a pair of "jets").

My final list of questions is:

- Are AGN jets hyper-relativistic? Radio jets exhibit bulk Lorentz factors $\Gamma \sim 10$; γ-ray burst models have taken us over the psychological hurdle to $\Gamma \sim 300$ which might just account for the reported radio variability of jets under the synchrotron model were it not to imply *steady* γ-ray burst level powers in AGN jets. Hence the appeal to coherent processes. Before we solve this problem, though, we must identify the jet working substance and if, and where, Poynting flux is transformed to plasma. (This last is still an interesting question in the case of the Crab pulsar wind.)

- Are jets better approximated as episodic or steady? Traditionally, we have modeled jets as stationary flows upon which have been imprinted perturbative disturbances which form shock fronts - the emitting elements. However, GRS 1915+105 suggest a quite different model - jets as a sequence of small explosions, perhaps associated with intermittent flow in the accretion disk, that expand into and keep open an evacuated channel. (YSO jets offer support to both views.)

- How are jets collimated? Ordered and disordered, poloidal and toroidal field have all been proposed for launching and collimating AGN jets from disks, just as with the YSO jets. 3D MHD global simulations are becoming increasingly ambitious and ever more relevant.

- Are relativistic jets powered by the spin energy of the hole or the binding energy of the accreting gas? The former seems more likely to form ultrarelativistic outflows; the latter may, on average, release more power. General relativistic numerical simulations are starting to guide our intuition.

- Why are there no gamma-ray megabursts? GRBs are thought to be associated with the birth of stellar black holes and produce powers of up to $\sim 10^{-7}c^5/G$ for $\sim 10^6 m$. If massive black holes are formed with masses $\sim 10^6$ $M_\odot$ at a rate of several per year, we might expect to see megabursts with similar powers but lasting for months. We don't. Perhaps, instead, massive black holes grow from much smaller holes, which, themselves, might be relics of the first generation of stars which may have masses $\sim 10^3 - 10^4$ $M_\odot$ at $z \sim 30$.

- How much do AGN contribute to the luminosity density of the universe? This is a closely related question. The measurement of the far infared background, the discovery of hard X-ray emission from some Seyfert galaxies and the spectrum of the X-ray background all point to AGN power being a significant fraction of the stellar luminosity density. If so, then there are probably implications for galaxy formation and development. For example, elliptical galaxies may result when a black hole grows rapidly and early in the life of the galaxy so that it is capable of blowing away late infalling gas before it can form a disk.

CONNECTIONS

As I hope this brief introduction has brought out, there are strong interconnnections between our studies of these different types of cosmic explosion. Accretion disk coronae can look quite like their solar counterpart. Novae have some dynamical similarities to miniature supernovae whose remnants, in turn, behave quite like aging γ-ray burst afterglows. Similar electromagnetic processes are at work around pulsars and black holes. γ-ray bursts themselves have some similarities, at least radiatively, with the early universe. And so on.

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