2002ASPC..263....1S

Stellar Collisions, Mergers and Their Consequences
ASP Conference Series, Vol. 263, 2002
Michael M. Shara, ed.

Stellar Collisions, Mergers and their Consequences

Michael M. Shara
American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024

Abstract. The apparent tranquility of the night sky masks the thousand pairs of stars that are colliding somewhere in the universe every hour. Some of these stellar collisions release so much energy that they can be detected at distances of a billion light years or more. Others produce distinctive remnants that are being found and characterized with HST, Chandra and other telescopes. This introductory overview outlines the main physical principles which determine the outcome of a stellar collision and recognizes some notable firsts in simulating collisions.

1. Introduction

Of all the ways for life on Earth to end, the collision of the Sun and another star would surely be the most dramatic. If the incoming projectile was a white dwarf star we would be treated to quite a fireworks show. The white dwarf would penetrate the Sun at hypersonic speed, well over 600 kilometers per second, setting up a massive shock wave that would compress and heat the entire Sun above thermonuclear ignition temperatures. Only an hour would be required for the white dwarf and its attendant shock wave to smash its way through our hapless parent star, but the damage would be irreversible. The superheated Sun would release as much fusion energy in that hour as it normally does during 100 million years. The resulting pressure would force the Sun to expand at speeds far above its escape velocity. Within a few hours the Sun literally would blow itself apart. And the source of this catastrophe, the white dwarf, would continue blithely on its way - not that we would be around long to care about the injustice of it all.

For much of the twentieth century the notion that stellar collisions might be worth studying seemed ludicrous to astronomers. The distances between stars in the neighborhood of the Sun are just too vast for collisions to occur. About 100 million Suns must be placed side by side to reach the nearest star, Proxima Centauri. The Sun and Proxima are moving at a very respectable 75000 km/hour with respect to their common neighbors. Nonetheless, their staggeringly large separation means that they have almost no chance of colliding during the 14 billion year history of our Galaxy. Other catastrophes will happen to the Sun (and Earth) in the distant future (astrophysicists are remarkably adept at doomsday scenarios), but a collision with a nearby star is not one of them. In fact, simple calculations carried out early in the 20th century by Sir

James Jeans suggest that not a single one of the hundred billion stars in the disk of the Milky Way galaxy has ever been involved in a collision with another star.

Just because our Sun is safe from the white dwarf doomsday scenario does not mean that collisions are uncommon. Quite the contrary has emerged in the past three decades, although even some astronomers are just beginning to realize the frequency and importance of stellar collisions in a variety of environments. It turns out that millions of pairs of stars have collided in and near our galaxy since it was created.

Some stellar collisions produce remnants with telltale structures forbidden by ordinary stellar evolution, and we have detected and begun to characterize these remnants. Dense star clusters have been identified as the sites of many stellar collisions. Collisions often lead to mergers that modify the stellar populations of clusters and their long-term evolution. Cataclysms seen halfway across the universe as powerful gamma ray bursts are also strong candidates for stellar collisions. Each of these topics is explored in detail in several of the contributions in these Proceedings.

The history of stellar collisions is extensively reviewed by Trimble (for stars in the field and in clusters) and De Young (for encounters in AGN) elsewhere in this volume. I'll concentrate here on three key conceptual breakthroughs vis-a-vis stellar collisions that occurred in 1975-76; the physical principles governing the outcomes of stellar collisions; an admittedly biased lists of "firsts" and "wows" in the 2-D and 3-D simulations of stellar encounters; and a few of the more pressing questions in our field that I hope to see answered in my lifetime.

2. Collisions in Globular Clusters 1975-76

1975-76 was a watershed period in the field of stellar collisions. Three simple but powerful concepts crystallized almost simultaneously: dense sites enhance the creation and detection of collision products, gravitational focusing increases collision frequencies and tidal capture can generate rare and exotic objects.

2.1. Dense Sites

By 1975 the UHURU satellite had led to the discovery of 10 luminous X-ray sources in the globular star clusters of our Galaxy, and about 100 other bright sources in the rest of the Milky Way. Katz(1975) pointed out that only 0.01% of the Milky Way's stars are in globular clusters, but fully 10% of our Galaxy's luminous X-ray sources are in clusters. Thus globular clusters are 1000 times overabundant in such sources relative to the rest of the Milky Way. Outside of globular clusters the simultaneous evolution of two newborn stars in a binary system succeeds in producing a luminous X-ray binary only about once in a billion tries. Inside globulars that ratio is one in a million.

A million stars in a cluster are crammed into a volume reserved for a hundred near the Sun. Given enough time the tightly packed stars will begin to collide. The stars are still small compared to the average distance between them, but Hills and Day (1976) showed that the probability of a collision is not just a simple matter of a star's physical cross section - gravitational focusing is an even more important effect.

2.2. Gravitational Focusing

Because the stars in a globular cluster move at a mere 10 or 20 km/sec, much lower than the speed of escape from their own surfaces, there is enough time in a close encounter for gravitational focusing to act. In this process (see the article by Davies in these proceedings for details) each of a pair of encroaching stars gravitationally deflects the path of the other towards itself. This results in effective collision cross sections (and thus collision rates) hundreds of times higher than those of naive calculations based on simple stellar geometric cross sections. In the densest central regions of some globular clusters, fully half the stars must have undergone one or more collisions since the creation of the universe. Strange stellar populations are likely to be the norm in such bizarre environments.

The effect is even more dramatic when a binary star is involved. Cross sections a million times larger than that of a single star are not unusual. Let's label the incoming binary's stars as A and B, while the encroaching single star is called C. In many cases, the three stars orbit each other dozens of times before the triple system breaks up. Star B may be swapped for star C, so that a new binary composed of stars A and C leaves the encounter, as does the newly divorced star B. Rare and exotic binaries, like X-ray sources difficult to produce via ordinary binary star evolution - are produced by these exchange interactions. It is also possible to gravitationally unbind all three stars, or to bind all three into a permanent triple system. Alternately, as Melvyn Davies emphasizes in these proceedings, any two or three of A, B and C may collide and merge.

2.3. Tidal Capture

Fabian, Pringle and Rees (1975) were the first to suggest that a grazing collision (or very near miss) could lead to the capture of an ordinary star by an isolated collapsar, in a process known as tidal capture. Close encounters involving three stars (usually a binary and a single star) are now believed to be even more effective in manufacturing X-ray sources. Tidal or 3-body capture probably increases nature's chances of making X-ray sources in dense star clusters a thousand-foldwhich neatly explains the puzzle raised by UHURU.

2.4. The Frequency of Collisions in the Universe

Because there are roughly 1000 billion globular clusters in the cosmos, and a collision between two Sun-like stars typically lasts for a few hours, we find that at least 1000 pairs of stars are undergoing a collision somewhere in the Universe right now! (This is a lower limit because I've ignored galactic nuclei and open clusters in this crude guesstimate.) The closest such event is, on average, about a billion light years away, explaining why no astronomer has yet identified a collision in progress. Nearby collisions must also occur, but they are rare. We expect a collision between two stars in a Milky Way globular cluster once in 10000 years.

2.5. What Unique Collisions are Possible?

There are seven distinct objects that most astronomers agree are stars, nearly stars, or stellar corpses. In order of decreasing density these are: black holes, neutron stars, white dwarfs, brown dwarfs, main sequence dwarfs, giants, and supergiants. Any of these seven types of stars can collide with any of the others, yielding 28 unique pairs of stellar encounters to consider. Because many collisions involve 3, 4 or more stars (most stars are in binary systems) which collide over a wide range of speeds and impact parameters, the variety of potential collisions is dauntingly large.

I have no doubt that somewhere/sometime in the Universe (probably in a populous star cluster), a giant-white dwarf binary orbited by a brown dwarf-red dwarf binary has encountered a supergiant-black hole binary bound to a neutron star companion. The initial conditions will determine who does what to who, and when. Hundreds of distinct outcomes are possible, and the fireworks during the mating dances must be astonishing.

2.6. The Outcome of Collisions

What happens when two stars collide? Just as in a collision involving two vehicles, the outcome depends on several factors. Most important are the speed of collision, impact parameter, and the structures of the colliding objects. There are stellar collisions that are fender-benders, others that are total wrecks, and everything in between. Higher velocity collisions, and nearly head-on collisions are best at converting kinetic energy into thermal energy and pressure, which can disrupt stars.

Fortunately, there are a few simple physical principles that govern what happens during collisions. Most important of these is density contrast. Simply put, the higher density star will suffer much less damage than the more tenuous of a pair during a collision.

2.7. Red Giants

Red giants involved in stellar collisions were first considered by Tuchman(1985) and Livne and Tuchman (1988). They pointed out the intriguing possibility of a spatial core-envelope separation in a red giant caused by its collision with a main-sequence star or white dwarf. This separation, which occurs in collisions with an impact parameter less than about 50 solar radii and with an impact velocity less than 360 km/s, leads to the loss of the entire envelope. Part of the envelope is dragged by the escaping core, while the rest of it disperses into space with typical velocities of 30 km/s.

2.8. Main-Sequence Stars

The case of two Sun-like stars was first simulated in 2-D by Cameron and Seidl (1972). As the initially spherical stars increasingly overlap they compress and distort each other into nearly half-moon shapes. Temperatures and densities never become high enough to ignite the disruptive thermonuclear burning accompanying a white dwarf MSS collision. A few percent of the total mass of the two stars is ejected perpendicular to the direction of stellar motion, but then mixing and overlap takes over. Within an hour or so the two incoming stars are

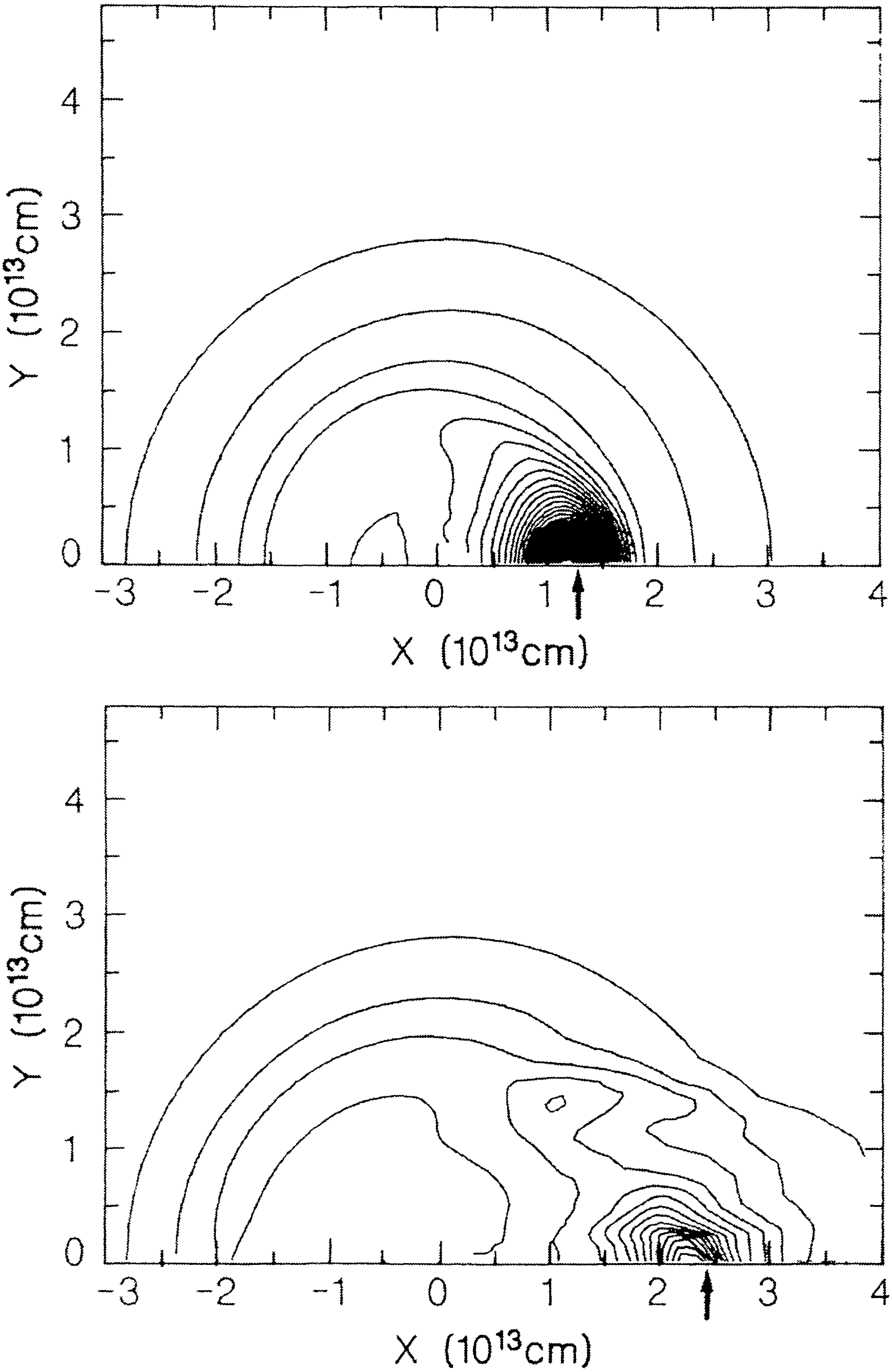

Figure 1. Equidensity contours in the red giant envelope during a red giant - nondegenerate star collision. The core's location is indicated by the arrow. (see Livne & Tuchman 1988)

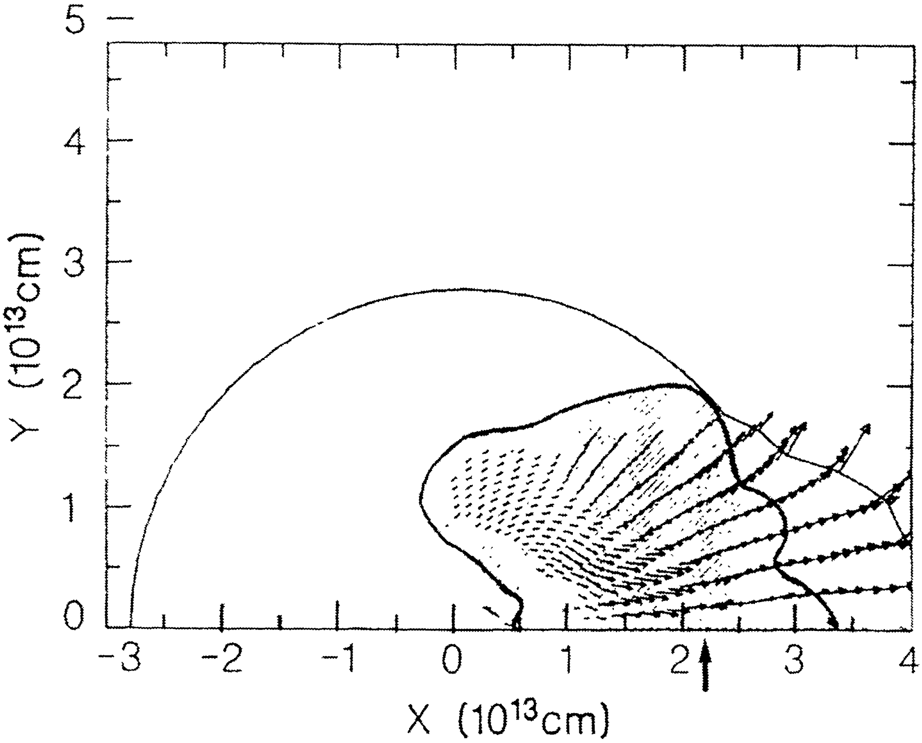

Figure 2. Velocity vectors during disruption of a red giant in collision. The core's location is indicated by the arrow. (see Livne & Tuchman 1988)

mixed together - fused for all time into a single, new star nearly twice as massive as its progenitors.

It is much more likely for two stars to collide somewhat off-axis, or in a grazing collision, than to hit each other exactly head-on. It is also more probable for the stars to be of slightly different mass than to be exact copies of each other. An off-axis collision of two MSS stars (first studied in detail by Benz and Hills (1987), and Lombardi, Rasio and Shapiro (1996) turns out to be a beautiful mating dance, resulting in the less massive but denser star burrowing to the center of its more massive but tenuous companion. The addition of fresh hydrogen fuel to the core of any sun-like star has a rejuvenating effect, rather like tossing twigs on a dying campfire. Thus the newly merged stellar object should appear more massive, more luminous and younger than either of its progenitors. It is also expected to be rapidly rotating, and to appear preternaturally young. Such a star, now called a Blue Straggler, should be commonplace in the cores of dense star clusters. This is one of the strongest predictions of stellar collision theory. Blue Stragglers are discussed extensively in this volume.

2.9. White Dwarfs

A head-on collision between a main sequence star (MSS) and a white dwarf (WD) was first simulated by Shara and Shaviv(1978) and Shara and Regev(1986). Mutual gravitational attraction accelerates the stars to well over 1000 km/sec as they approach each other on a collision course. The shock wave and compres-

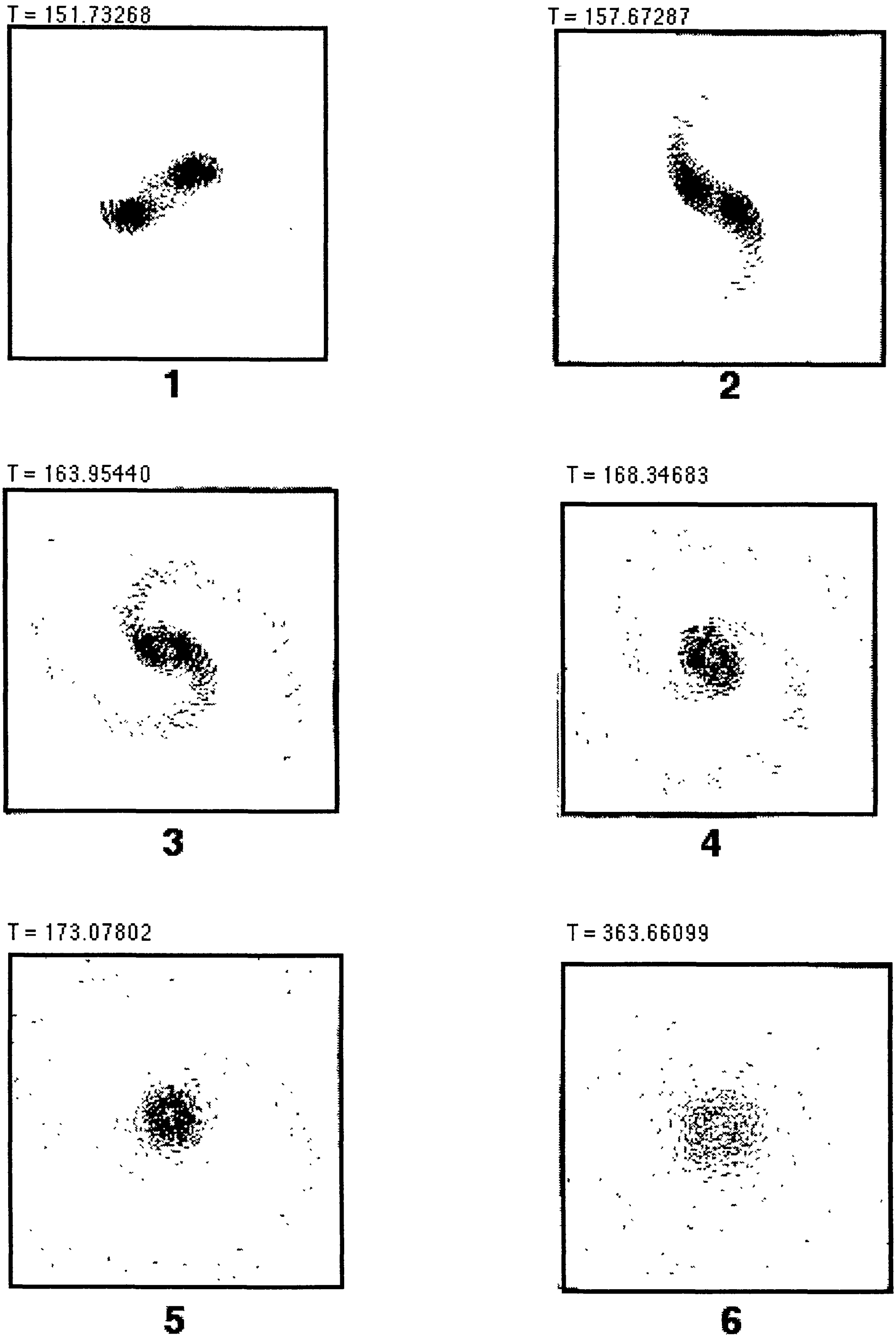

Figure 3. An off-axis collision between two main sequence stars. The first 5 frames are "snapshots" of the two stars at increasing times during second periastron passage. The last frame shows the system long after the collision. (see Benz & Hills 1987)

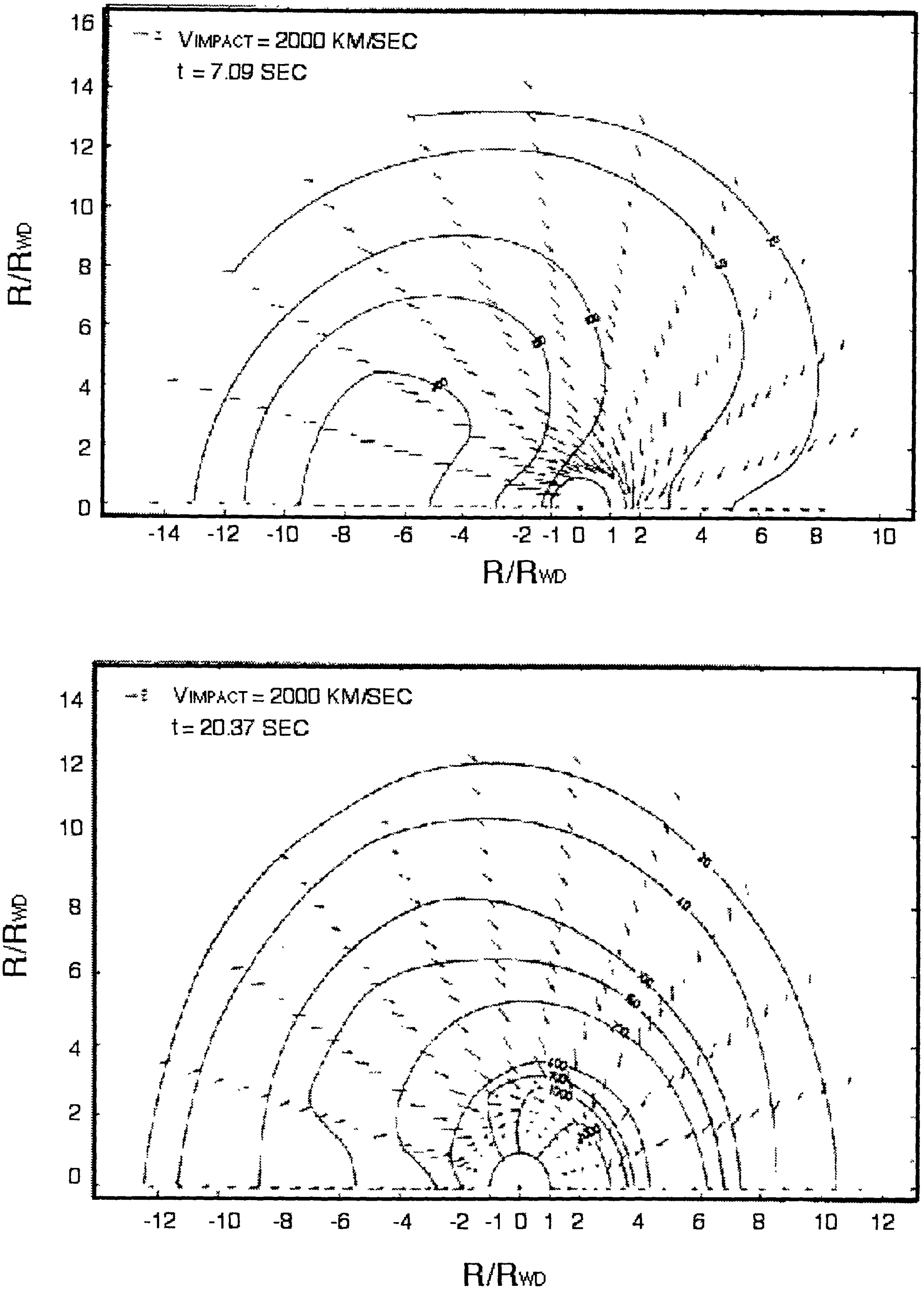

Figure 4. A white dwarf - main sequence star head - on collision. Top Panel: Configuration of the 2000 km/s impact velocity collision at machine time t = 7.09 sec. Bottom Panel: Later in the same collision, t = 20.37 sec. (see Shara & Shaviv 1978)

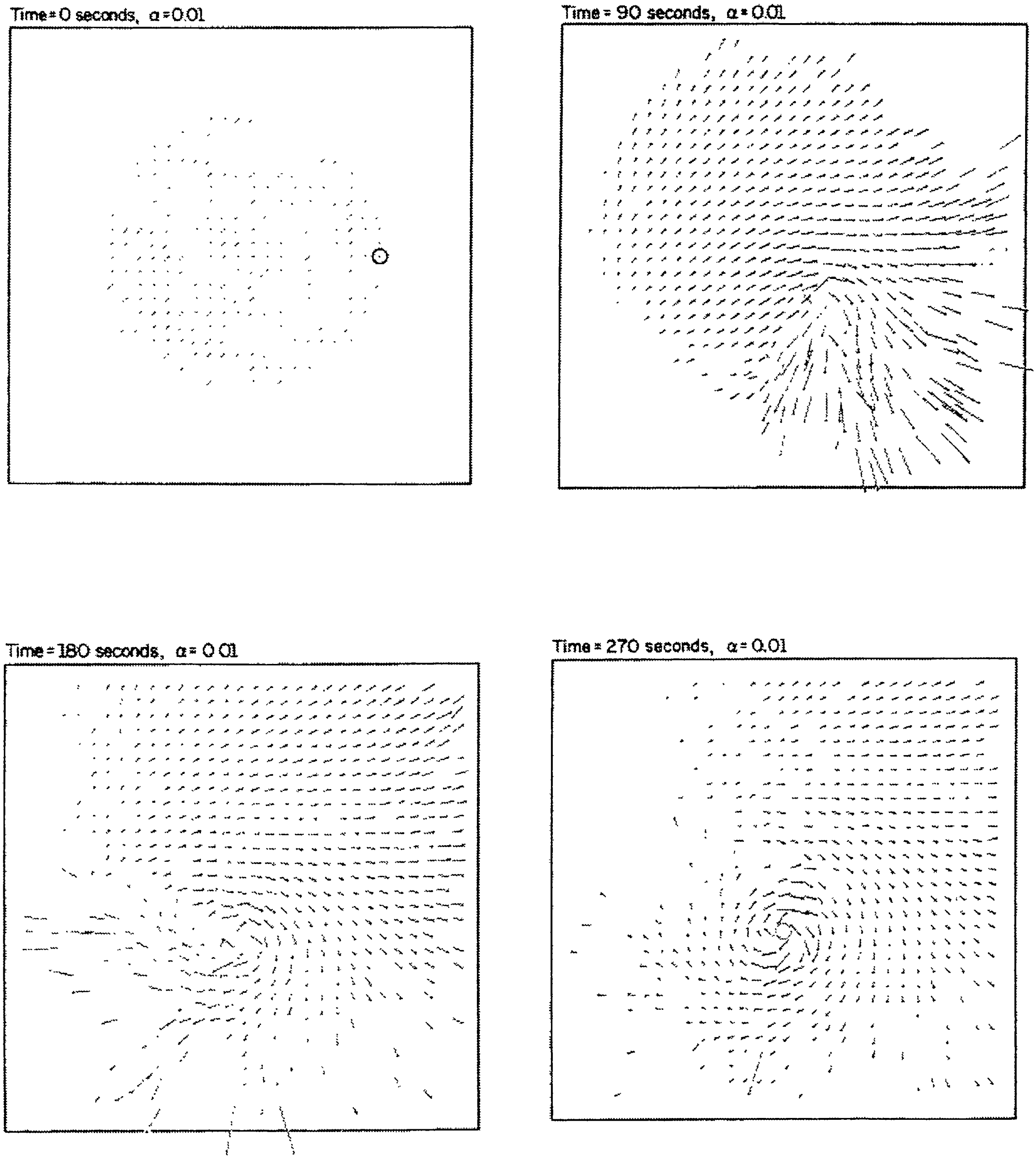

Figure 5. An off - axis white dwarf - main sequence star collision. The projected velocities onto the place subtended by the initial velocity of the main-sequence star and the line joining the centers, at the time of contact. The white dwarf is represented by the open circle. Top Left: Initial contact at t = 0 sec. Top Right: t = 90 sec after contact. Bottom Left: t = 180 sec after contact. Bottom Right: t = 270 sec after contact. (see Soker, Regev, Livio & Shara 1987)

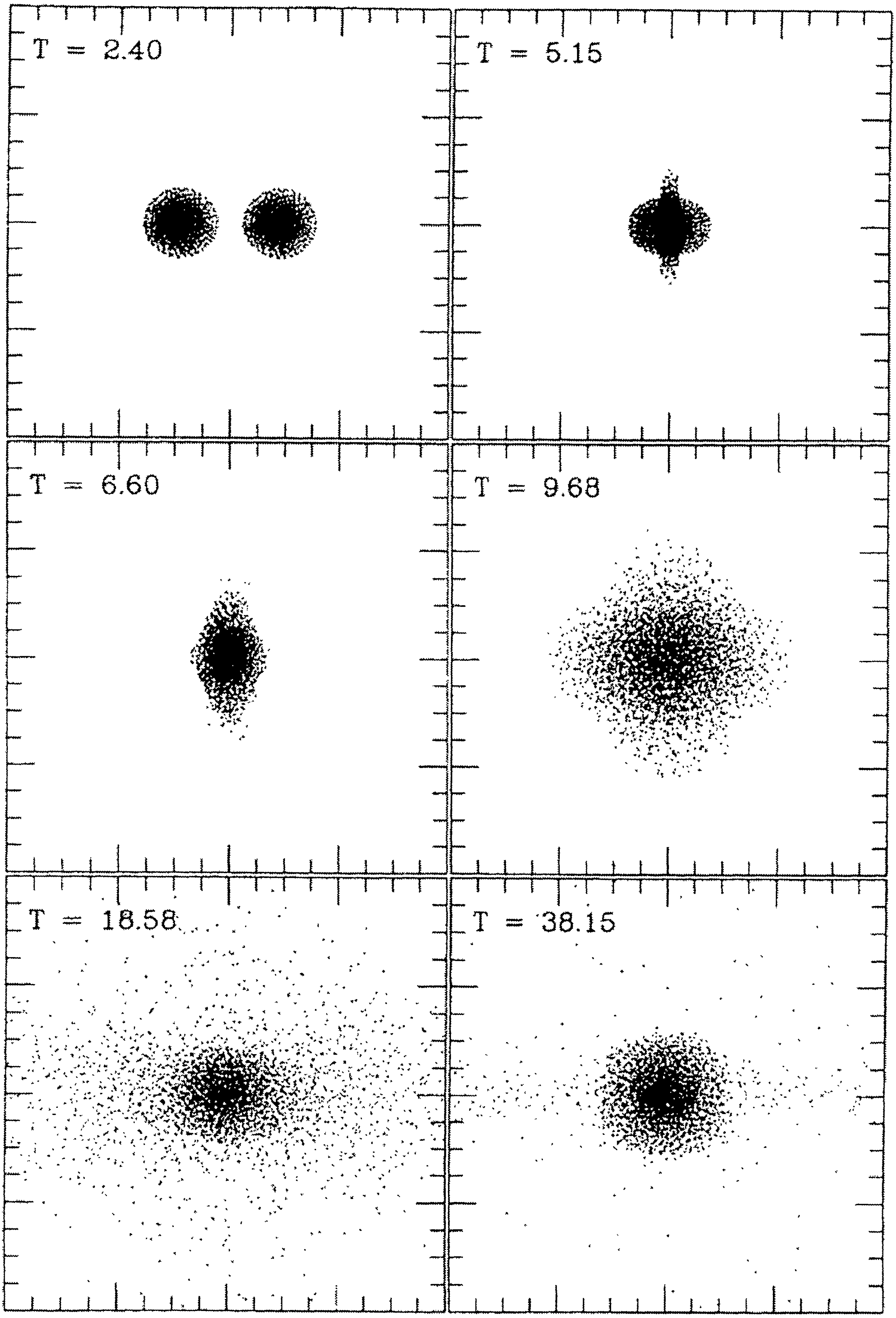

Figure 6. Projection onto the plane of the initial orbit of the fluid particles in two colliding white dwarfs at various times during a head-on collision. The times are in seconds from the begining of the simulation. (see Benz, Hills & Thielemann 1989)

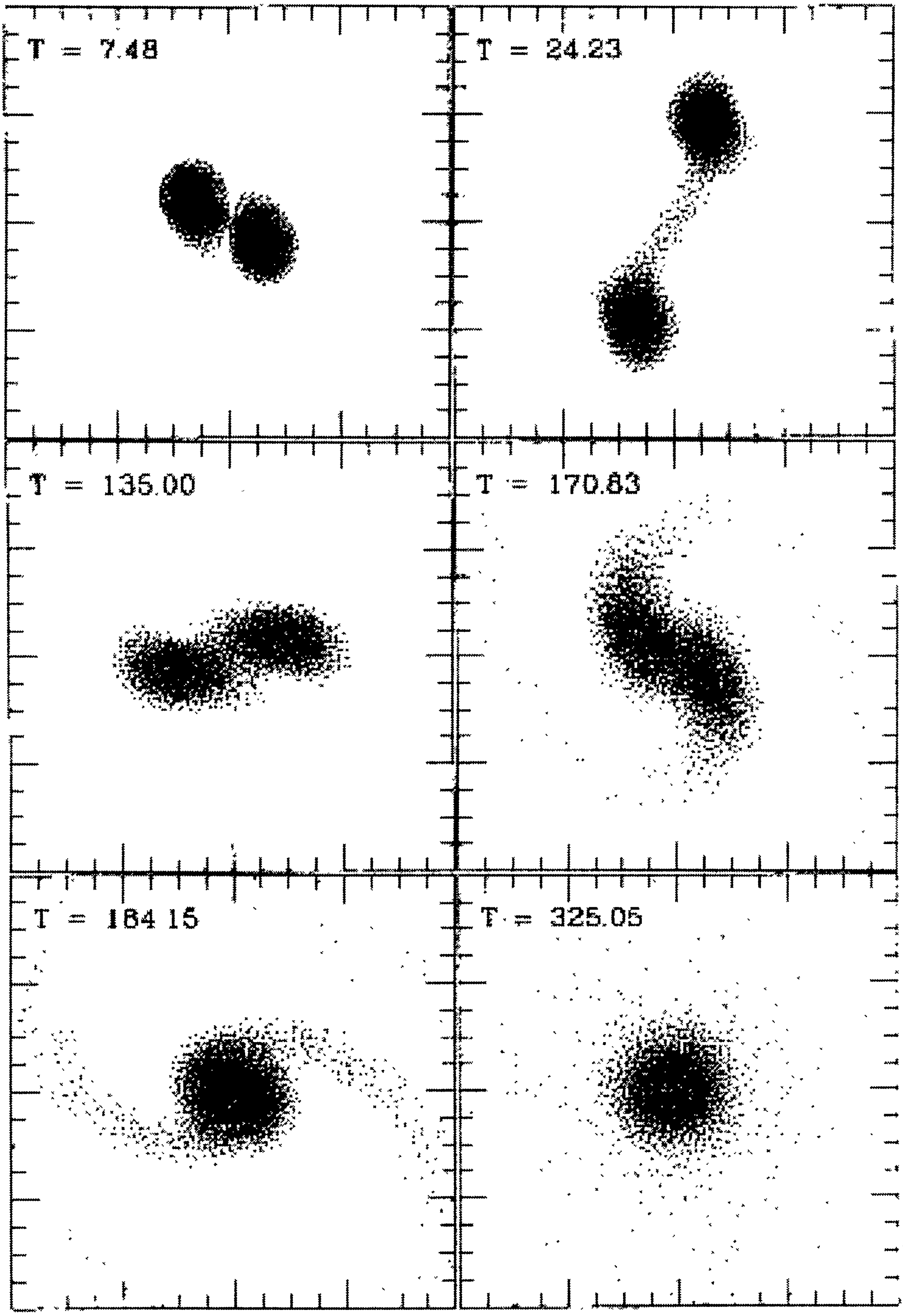

Figure 7. Projection onto the plane of the initial orbit of the fluid particles position at various times during a collision between two white dwarfs with masses of 0.6 $M_\odot$ each and with $R_{min}/(R_1 + R_2) = 0.772$. (see Benz, Hills & Thielemann 1989)

sional heating that propagates through the MSS heat it to over 10^8 deg K, leading to immediate proton capture by every CNO nucleus in the star. The resulting energy released exceeds the MSS binding energy by factors of 5 or more, causing the MSS to rapidly expand and disperse. The white dwarf escapes with only its outermost layers warmed by the disrupted MSS and nuclear conflagration it leaves behind. Except for an anomalously high surface abundance of nitrogen the white dwarf should appear unchanged, so this scenario is difficult to test observationally.

A grazing WD-MSS collision, first modeled by Soker, Regev, Livio and Shara (1987) suggested that a massive disk, in orbit around the white dwarf, should form from the disrupted MSS. If massive disks are stable (a big if!) then an exotic, new class of astrophysical object - massive disk stars (or MDS) may exist. No MDS has yet been shown to exist, though some might be masquerading as mass transferring binary stars in star clusters.

The first simulations of colliding white dwarfs were presented by Benz, Thielemann and Hills (1989). Their 3-D numerical simulations used an SPH code with 5000 particles. The code allowed for radiation and degenerate pressure and used a reduced nuclear network which models the large release of nuclear energy. In nearly head-on collisions, a very substantial fraction of the mass was lost as a result of a large release of nuclear energy. In grazing collisions, the fraction of mass lost was close to that produced in collisions between main-sequence stars. The quantity of processed elements ejected into the ISM by these collisions was not found to significantly affect the chemical evolution of the Galaxy. Grazing collisions gave rise to massive, merged WDs, including some rapidly rotating models in excess of the Chandrasekhar mass. These would presumably collapse after dissipation of sufficient heat and angular momentum.

2.10. Neutron Stars and Black Holes

Lattimer and Schramm (1974) first considered the tidal breakup of a neutron star near a black hole. A simple model for the interaction was calculated, and the results show that the amount of neutron-star material ejected into the interstellar medium may be significant. The estimated quantity of ejected material was found to be roughly comparable to abundances of r-process material.

Symbalisty and Schramm (1982) noted that a natural consequence of a binary pulsar's evolution is a neutron star collision. Such a collision is expected to eject neutron-rich matter of an r-process character. Taking estimates for the number of such events over the history of the galaxy, they concluded that they could account for all of the r-process nuclei in the Galaxy.

Sikkema and Israel (1991) considered merging black holes. As the black hole formed by the collapse of a rotating star settles down, it absorbs part of the gravitational radiation emitted during the last moments of collapse. This radiation, strongly blue-shifted near the inner horizon, enormously increases the mass of the black hole's core. External observers cannot detect this mass, but it manifests itself dramatically when black holes merge. Black hole collisions are described in detail by Shapiro in these proceedings.

Ruffert and Janka (1999) and these proceedings carried out 3-D hydrodynamic simulations to investigate the formation and the properties of the accretion torus around a stellar mass black hole which they assume to originate from

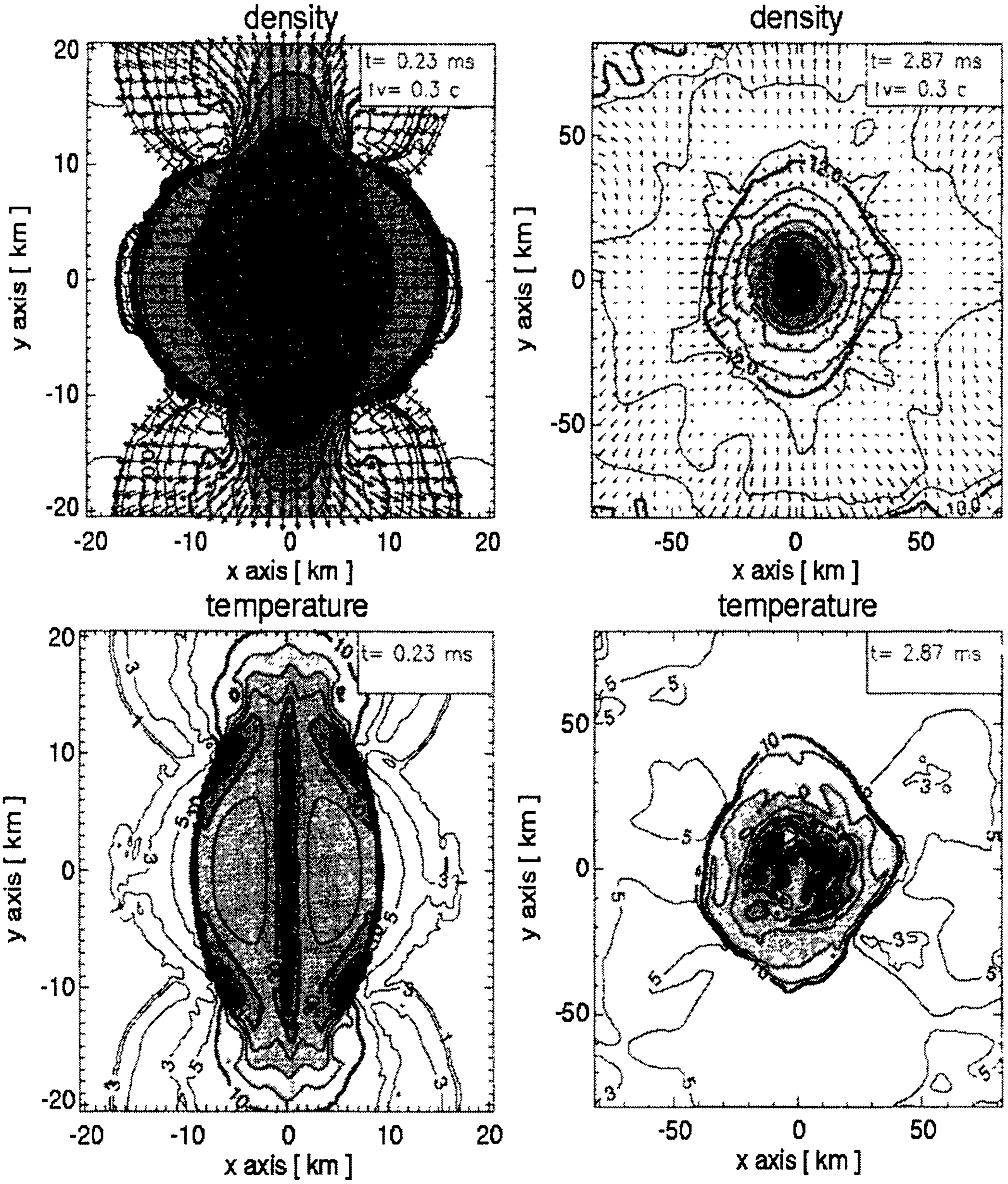

Figure 8. Contour plots of two models (left and right) of colliding neutron stars. Panels a and b display density with the velocity field. Panels c and d display the temperature. (see Ruffert & Janka 1998)

the remnant of a neutron star merger. They include the use of a physical equation of state as well as the neutrino emission from the hot matter of the torus. They find that the torus formed after neutron star merging has a mass of roughly $0.03 - 0.3$ solar masses with maximum densities around 10^{12} g cm^{-3} and maximum temperatures of about 10 MeV. Correspondingly, the neutrino emission is huge with a total luminosity near 10^{53} erg s^{-1}. Neutrino-antineutrino annihilation deposits energy in the vicinity of the torus at a rate of $(3 - 5)x10^{50}$ erg/s. It is most efficient near the rotation axis where 10 to 30% of this energy or up to a total of 10^{49} erg are dumped within an estimated emission period of $0.02 - 0.1$ s in a region with a low integral baryonic mass of about 10^{-5} solar masses . The conversion of neutrino energy into a pair plasma is sufficiently powerful to blow out the baryons along the axis so that a clean funnel should be produced within only milliseconds. The models show that accretion on the black hole formed after neutron star merging can yield enough energy by neutrino-antineutrino annihilation to account for weak, short gamma-ray bursts, if moderate beaming is involved

2.11. Observations of Stellar Collision Products

It is gratifying (and somewhat amazing to me) that some of the predicted by-products of stellar collisions have now been detected by the Hubble Space Telescope, in the cores of several dozen globular clusters orbiting the Milky Way and a few neighboring galaxies. Djorgovski et al (1991) have noted a decided lack of red giant stars near the cores of globular clusters, possibly due to envelope stripping. Blue Stragglers, a puzzling oddity when first discovered by Sandage (1953), are now recognized as phoenix-like, reborn stars - prime examples of stellar coalescence. Shara, Saffer and Livio (1997) and Saffer (these proceedings) measured Blue Straggler masses with twice and three times the mass of the most massive stars in their clusters, a strong indication of stellar coalescence.

The existence of blue stragglers, and their large masses, the overabundances of X-ray sources and other exotic binaries, and the dearth of red giants all strongly support the hypothesis that stellar collisions and mergers can and do occur in star clusters. Only if we are extraordinarily lucky will a direct collision occur close enough (say, within a few Million parsecs of Earth) within the lifetimes of today's astronomers to be directly observable with optical or X-ray telescopes. LIGO and LISA are much more likely to provide the first direct observations of a stellar collision as it unfolds.

3. Conclusions

The observational and theoretical pictures that emerge from this meeting are far from complete. Some types of stellar collisions, particularly those involving black holes or neutron stars, may yield very exotic objects, or enormous energy releases associated with the still poorly understood gamma ray bursts. The fates of planets orbiting colliding stars are just beginning to be considered. Studies involving multiple collisions in groups of stars which lead to super-massive stars are also barely underway. The eventual dissolution of ancient globulars may be largely driven by near-collisions which fling stars at high speeds out of these ancient fossil clusters.

The progress of the last generation in this field has been astonishing, but the best is yet to come. I'm convinced that the technologies of astronomers a generation or two from now will allow direct and routine detections of stellar collisions, and stringent observational tests of stellar collision theory.

References

Benz, W. & Hills, J.G. 1987, ApJ 323, 614

Benz, W., Thielemann, F.-K. & Hills, J. G., 1989, ApJ 342, 986

Cameron, A.G.W. & Seidl 1972, Ap & SS 15, 44

Djorgovski, S., Piotto, G., Phinney, E. S., & Chernoff, D. F. 1991, ApJL, 372, L41

Fabian, A,C., Pringle, J.E. & Rees, M.J. 1975, MNRAS 172, 15p

Hills, J.G. & Day, C.A. 1976, ApJL 17, 87

Jeans, J. 1928, in Astronomy and Cosmogony, pp 319, Dover, New York (1961)

Katz, J.I., 1975, Nature 253, 698

Lattimer, J.M., & Schramm, D.N., 1974, ApJ 192, L145

Livne, E. & Tuchman, Y. 1988, ApJ 332, 271

Ruffert, M. & Janka, H.-Th. 1999, A&A 344, 573

Ruffert, M. & Janka, H.-Th. 1998, A&A 338, 535

Sandage, A. R. 1953, AJ 58, 61

Shara, M. M., Saffer, R. A., & Livio, M. 1997, ApJL 489, 59

Shara, M. M. & Regev, O. 1986, ApJ 306, 543

Shara, M. M. & Shaviv, G. 1978, MNRAS 183, 687

Sikkema, A. E. & Israel, W. 1991, Nature 349, 45

Soker, N., Regev, O., Livio, M. & Shara, M. 1987, ApJ 318, 760

Symbalisty, E. & Schramm, D.N., 1982, ApJL 22, 143

Tuchman, Y. 1985, ApJ 288, 248