Title
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Journal
ASTROPHYSICAL LETTERS & COMMUNICATIONS, 22(1)

ISSN
0888-6512

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Publication Date
1981

Astrophysical Letters, 1981, Vol. 22, pp. 21–30
0004-6388/81/2201-0021$06.50/0

Relativistic Astrophysics: The View from Texas in Baltimore (*Review*)

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(*Received July 7, 1981*)

INTRODUCTION

The phrase "relativistic astrophysics" was invented by Ivor Robinson, the late Alfred Schild, and Englebert Schucking on July 4th, 1963, as part of the title of a symposium they were then organizing at Dallas ("Conference on Gravitational Collapse and Other Topics in Relativistic Astrophysics"). The glory of the name, according to Robinson (who claims to have been out of the room at the crucial moment), was that no one knew what it meant, so they could have anything they wanted at the conference. This tradition has been nobly maintained over the subsequent series of ten "Texas" Symposia on Relativistic Astrophysics, though they have strayed as far from Dallas as Munich and, most recently, Baltimore (December 15–19, 1980). Although the phrase has gradually evolved to comprehend astronomical phenomena that either involve very high energies (total or per particle) or require physics beyond Newton's laws and Maxwell's equations for their explication, anything that sounds exciting as December of an even-numbered year rolls around automatically becomes relativistic astrophysics by definition. We outline here some of the recent observations and theoretical work incorporated into the latest symposium.

THEORETICAL UNDERPINNINGS

Is General Relativity the right theory of gravity? Well, yes and no, most relativists would say, simultaneously, and not so inconsistently as it first sounds. Yes, in the sense of being the right classical theory, agreeing with all available observations, and in being the inevitable result of a force carried by a spin-2, massless boson (the graviton). But no, in the sense that general relativity is not a quantum theory and cannot be turned into one. It is not renormalizable. That is, many seemingly sensible calculations yield infinite answers, and there is no coherent prescription for subtracting the infinite part to leave a finite, correct answer, in the way that quantum electrodynamics deals with the infinities of electromagnetism.

Even at the classical level, there may be lingering doubts: Thomas Van Flandern (U.S. Naval Observatory) finds, primarily from precise timings of lunar occultations, that the constant of gravity is decreasing by 3 parts in 10^{11} per year, which is certainly not predicted by GR. The formal error on this number is very small; but the systematic errors probably include zero at the 1σ level.

The quantum problem has long been with us. Bryce DeWitt (Univ. Texas) one of the pioneers of the field, noted that without quantum gravity we cannot hope to understand particle production in time-varying geometries (either in the early universe or around black holes), the big bang, the nature of the vacuum, or whether or not the singularities of GR must be taken seriously. He is not optimistic about a rapid solution to these problems. Others are more sanguine. Yuval Ne'eman (Tel Aviv University) described recent progress in supergravity, the theory in which two particles, the graviton and a spin 3/2 fermion called the gravitino, carry the gravitational force in such a way that their infinities tend to cancel each other. Finiteness has, so far, been demonstrated for the calculations that correspond to Feynman diagrams with up to two loops (including matter and electromagnetic fields), by which level GR has already broken down, and for special cases of larger numbers of loops. Positive definiteness and the right kind of symmetry breaking have also been demonstrated.

The grail on the horizon is the possibility of unifying (super) gravity with the other three interactions to achieve, at long last, Einstein's goal of a unified field theory. Ne'eman and others have expressed high hopes for an $N = 8$ supersymmetry. Perhaps the most worrisome feature at the moment is that the particle-like entities in the supersymmetry are not numerous enough to correspond to the quarks and leptons we see, which must, therefore, be made up of other, more fundamental, constituents.

Meanwhile, back at the classical GR ranch, important problems remain unsolved. Gravitational radiation from a pair of orbiting point masses (like the binary pulsars and nova-like systems) is customarily calculated using a weak-field, quadrupole formula from Landau and Lifschitz. The orbit size of the shortest-period binary pulsar is decreasing at about the rate predicted by this formula (if there are no other important effects on the system), which would seem to show that the formula is right. But the theorists are not so sure. About half a dozen groups have attempted to calculate the flux of outgoing gravitational radiation for this case, using either equations of motion or matched asymptotic expansions. They divide almost equally among "quadrupole formula wrong," "quadrupole formula right," and "cannot tell at this stage." Factors of two or more between the quadrupole formula and the right answer are not impossible.

Similarly, the general relativistic "corrections" in calculations by Stan Woosley (UC Santa Cruz) and others of the duration and luminosity of X-ray bursts caused by accretion and nuclear burning on the surfaces of neutron stars can amount to factors of two or more, and are by no means negligible. At least in these cases, there is no disagreement about how to do the relativistic part of the calculations!

Exact solutions of Einstein's equations that apply to physically realizable situations remain few. But Tsvi Piran (Inst. for Advanced Study) suggests that we now have at least approximate, ad hoc solutions for most of the interesting cases, like gravitational radiation from the collapse of isolated objects and the collisions of pairs of black holes. Most of these solutions have been achieved by numerical rather than analytic methods. Perhaps the biggest surprise is how much of the total mass-energy can be radiated away—up to 25% as a distorted black hole relaxes to a Schwarzschild or Kerr configuration, and up to 65% from collapsing cylindrical systems (which, of course, don't exist, but may be a fair approximation to real objects with large deviations from spherical symmetry)—compared to much less than 1% found some years ago for head-on collisions of Schwarzschild black holes.

In the same approximate spirit, Larry Smarr and Michael Smith (Univ. Illinois) with James Wilson and Michael Norman (Lawrence Livermore Lab) have applied numerical methods to a magnetized, rotating accretion disc around a nonrotating black hole. They find that, while lots of matter falls in beyond recall, a small amount spurts out in relativistic jets at an angle of about 45° to the field. The jets are stable over a rather restricted energy range, tending otherwise to break into blobs and bubbles. More accurate treatment of gas and field parameters may make something that looks still more like the twin gas jets required in some models of active galaxies.

Perhaps the most exciting theoretical development since the last Texas Symposium is the general recognition of a close coupling between grand unification and several astronomical and cosmological issues. Many discussions of unification (of the electromagnetic and weak interactions) and grand unification (of the electromagnetic, weak, and strong interactions) have appeared (*e.g.* Refs. 1–3). Two of the important astrophysical aspects are:

1. Spontaneous symmetry breaking can be blamed for the excess of matter over antimatter throughout the universe, or, according to Floyd Stecker (Goddard Space Flight Center) for an excess of matter in our neck of the woods and antimatter in other regions, 10 million or so parsecs away. This is the characteristic size scale of superclusters of galaxies, and, in Stecker's view, annihilation at the interfaces between regions is responsible for at least some of the observed gamma ray background. In the more usual view, as outlined by Sydney Bludman (Univ. Pennsylvania) and David Schramm (Univ. Chicago), an excess of matter should appear throughout the universe, provided that there is violation of CP invariance, non-conservation of baryons (as in the GUT's), and absence of thermodynamic equilibrium. The amount of the excess, as expressed by the average photon-to-baryon ratio ($10^{9\pm1}$), is coupled in principle to the lifetime of the proton, but Edward Kolb (Los Alamos National Laboratory) noted that the relationship (including even its sign) is

very sensitive to details of the theory. Experiments now in progress to measure that lifetime (Ref. 4) are, therefore, by no means superfluous.

2. Non-zero-rest-mass neutrinos may, as remarked by Cowsik and McClelland (Ref. 5), dominate the mass-energy density not only of the universe as a whole but also of individual galaxies and clusters, provided that there is a background sea of neutrinos corresponding to the 3 K sea of photons. Two recent experiments (an examination of the end-point of the Kurie plot for tritium decay, carried out in Moscow, and a search for neutrino oscillations, carried out at the Savannah River reactor by a group from UC Irvine) are suggestive of rest masses, for at least one neutrino, in the range permitted by earlier work ($\lesssim 50$ eV) but still large enough to be astronomically interesting ($\gtrsim 1$ eV). Such neutrinos, as discussed by A. Szalay (Roland Eotvos University, Budapest), Humitaka Sato (Kyoto Univ.), David Schramm (Univ. Chicago) and others, may close the universe, bind clusters of galaxies, and be responsible for the dark mass in extended halos around the Milky Way and other galaxies. It is not very easy to get a single neutrino mass to do all the interesting things, but as there are at least three kinds of neutrinos to play with, this need not be a problem.

More detailed calculations of galaxy formation and so forth in the presence of massive neutrinos must await more conclusive laboratory measurements of the (several) masses. And so, although one distinguished senior theorist was prepared to bet (at breakfast and, therefore, presumably, in doughnuts) five to one against the mass of the neutrino being anything but zero, we would be foolish to say more now.

COSMIC BACKGROUNDS

Although one normally thinks of astronomy as being the study of discrete objects in space, a surprising amount of information can be derived from photons and other particles that reach us (almost) isotropically. The best- (though not the longest-) known background is that of microwave photons, representing thermal radiation at a temperature near 3 K. Small deviations from a black body spectrum, in the sense of too few photons at short wavelengths and too many near the peak, have been known for several years. Joseph Silk (UC Berkeley) reported both new data (from Gursky *et. al.*) confirming the deviation and several mechanisms to produce it. These include free-free emission near a redshift of 1000 and reradiation of pre-galactic starlight by dust at a redshift near 100. Small deviations from isotropy also appear in the microwave background. The well-known dipole anisotropy is normally interpreted as motion of the Local Group at about 600 km/sec relative to the matter that last scattered the photons. In addition, a quadrupole anisotropy and fluctuations on angular scale ~ 6° have been reported (at about the 4σ level) by R. Fabbri (Univ. of Florence). Steve Boughn (Princeton Univ.) has also seen a quadrupole term (at ~ 0.5 mK and ~ 4σ confidence level) in a recent balloon experiment. Such a quadrupole term could be produced either by rotation and shear in the expansion of the universe or by lumpiness in the mass-energy distribution of a kind consistent with Jim Peebles' (Princeton Univ.) measurements of galaxy clustering.

There is also a well-defined, nearly isotropic X-ray background. It shows a quadrupole moment (presumably attributable to a density enhancement further from us than the source of the photons) and little other variation with direction. This smoothness provides a stronger constraint on density fluctuations over some size scales (*e.g.* $\delta\rho/\rho < 0.1$ to 0.01 for scales of 100 to 1000 Mpc) than does the microwave background. The main controversy is over whether the X-ray background is mostly genuinely diffuse (and produced by widely distributed hot intergalactic gas) or primarily the sum of many distant sources (like quasi-stellar objects and Seyfert galaxies). Confusingly, the spectrum, as reviewed by Andy Fabian (Cambridge Univ.) looks thermal (with a temperature of 40–50 keV) but shows no evidence of the iron emission feature universally associated with hot gas in clusters of galaxies. A suitable superposition of sources, at least some of them with non-thermal spectra like 3C 273, but at larger redshifts, could also match the data, if there are enough of them. This is largely a question of how much more common (if at all) such sources were in the past than they are now. Plausible guesses can yield anywhere from 3% to 90% of the observed background. The issue must be resolved by careful source counts at (and perhaps beyond) the faint limit of Einstein Observatory pictures.

The hard photon background persists into the gamma ray region, though with a change in spectral shape near 1 MeV. Again, it is not clear how much is due to distant sources and how much to matter anti-matter annihilation or other diffuse processes. The galactic component of the background is clearly diffuse and can be used to trace out gas and cosmic ray densities within the Milky Way disc. The extragalactic component (assuming that isotropy in galactic coordinates implies production at large distances) is still up for grabs.

When we come to the extragalactic ultraviolet background, the most important question is whether or not it even exists. If it does, Richard Henry (Johns Hopkins Univ.) points out that it will provide valuable information about warm-to-hot intergalactic gas (or limits thereon). The problem is to subtract accurately enough from the observed fluxes (which themselves still have large error bars attached) uv radiation emitted, reflected, or scattered by the atmosphere, interplanetary and interstellar dust, stars, and so forth. More extensive observations from above the atmosphere should help.

A nearly isotropic flux of relativistic nuclei and electrons undoubtedly strikes the earth. The only things we don't know about these cosmic rays are (a) where and how are the nuclei synthesized? (b) how do they get accelerated to high energies? and (c) how do they propagate through the galaxy to us? Their chemical and isotopic composition ought to constrain all three. Hydrogen and helium have long been known to be deficient in the cosmic rays (or, alternatively, everything else is enhanced). Apart from this, differences from normal solar composition, once corrections are made for spallation during propagation, are few and far between, though there have been many false alarms. Ed Stone (Caltech) reported convincing evidence for 50% excesses of the neutron-rich isotopes Mg^{25}, Mg^{26} and Si^{30}; while Ne^{22} is high by a factor of 2.5–3.0 (though its "normal" abundance is not very well defined). He suggested that no other anomalies have been clearly demonstrated among either the elements lighter than iron or those heavier. They must, in any case, be rather small. Ian Axford (Max Planck Inst. Aeronomy, Lindau) interprets the rather normal cosmic ray source composition (along with spectrum, age, and total energy density) to mean that acceleration must occur well away from the objects doing the nucleosynthesis. He advocated acceleration by supernova shock waves in the general interstellar medium. Other speakers favored acceleration in discrete events, close to compact objects, as being better able to account for the near-constancy of the LiBeB to CO abundance ratio as a function of energy. In either case, the hardest part seems to be injection—getting the particles up to moderate energies so that efficient acceleration processes can take hold. David Eichler (Univ. Maryland) addressed this problem, proposing a self-regulating mechanism with the virtue of depending on A/Z in such a way as to keep H and He low, while leaving other relative abundances more or less unchanged. Gaurang Yodh (Univ. Maryland) remarked that the ratio of iron to H has reached 45% at 10^{16} eV and may be nearly 100% at still higher energies. This should provide a crucial test for any injection/acceleration mechanism, although these very high energy cosmic rays cannot be confined within our galaxy and so need not be produced here.

Finally, Guido Pizzella (Inst. of Physics, Rome) reported data analysis for gravitational wave antennas in Rome and Frascati which suggests that there is a (very crudely isotropic) background of something that simultaneously excites pairs of massive aluminum bars at liquid helium temperatures, even when they are far apart. The excitation events occur with temporal separations characteristic of the earth's normal modes (though not at the same time as particular excitations of earth-interior or geomagnetic oscillations). Similar temporal structure has been found retroactively in earlier gravitational radiation antenna data reported from the University of Maryland.

COSMOLOGY AND GALAXY FORMATION

Within the framework of conventional cosmology (the study of homogeneous, isotropic, general relativistic models having no cosmological constant), the universe is uniquely defined by two numbers, the current expansion rate, H_0, and the current average density of mass-energy, ρ_0 (or Ω_0, which is ρ_0 divided by the critical value just needed to close such a universe). The first of these numbers, H_0, after gradually shrinking from 500 to 50 km/sec/Mpc over the last 40 years, implying a time scale for the university which has grown from 2 to 20 billion years—and no wonder we're all so tired if we've been studying cosmology for 18 billion years—has started to grow again. Gerard de Vaucouleurs (Univ. Texas) explained with great care how his system for measuring distances to galaxies far enough away to calibrate H_0 works. It involves many different, independent distance indicators, consistency checks among them, and the largest possible number of calibrating objects at each link in the chain from 1 AU to 10 Mpc. Many of us do not like his value ($H_0 = 100 \pm 10$ km/sec/Mpc) as the associated time scale is perilously short even for a low-density universe (10 billion years) and downright embarassing for a closed model (less than 6.7 billion years, about the age of open star clusters like M67). But this is our problem rather than his!

Geoffrey Burbidge (Kitt Peak) presented a wonderful zoo of pairs and groups of galaxies, qso's, and what-nots (mostly found by Halton Arp and Cyril Hazard) that look like they are close together, but have wildly different redshifts, making one wonder whether a distance scale even exists. In all cases, the smaller (angular diameter) or more compact objects have the larger redshifts, and there are assorted complex correlations of position, luminosity, and redshift of the objects in some groups. Interpreting these is a matter of some discord and clearly will remain so until other observers do correspondingly thorough searches of other regions of the sky and convince themselves that the zoo objects either are or are not statistically significant independent of who found them and how. Even if the wild groups turn out to be real, Martin Rees (Cambridge Univ.) pointed out that all is not lost for the conventional wisdom. Certain kinds of relativistic jets near massive black holes may actually be capable of expelling appreciable fractions of a galactic mass at usefully large speeds. Unfortunately, a component coming toward us will always look much brighter than one going away, suggesting that the majority of the zoo objects must be at the large distances corresponding to the redshifts of the compact bits and the normal galaxies have been thrown out of them. The model requires further work.

The second critical number, the local mass-energy density, is even less well known than H_0. The luminous matter seen directly in galaxies contributes an Ω_0 of only about 0.01. This must be ordinary baryonic matter. If we want to synthesize the observed amounts of deuterium and helium within a standard-model early universe, then the total amount of baryonic material cannot be more than about 10% of the closure density. Low mass stars in extended galactic halos could easily contribute this much. The density in non-visible non-baryons may be considerably larger, and is surely considerably harder to measure or constrain. Fritz Zwicky first demonstrated about 50 years ago that rich clusters of galaxies must have hidden mass in them, as they are surely gravitationally bound systems, and their Virial masses are 10 to 100 times larger than the sum of their visible galaxy masses. Peebles, Amos Yahil (SUNY, Stony Brook), and Richard Harms (UC San Diego) and Holland Ford (UC Los Angeles) have applied similar but more elaborate analyses to clusters and superclusters and find "most probable" values of Ω_0 of 0.5, 0.12, and 0.06–0.12 respectively, for all forms of mass-energy associated with galaxies. What is it made of? Low mass stars, clumpy gas, planets, brick bats, and neutron stars and black holes made by massive stars are all possible if the deuterium argument can be evaded. Otherwise, the only candidates seem to be primordial black holes and massive neutrinos.

The neutrino-dominated case has interesting implications for two other classical cosmological problems—the nature of the initial singularity and the kinds of fluctuations that can evolve into galaxies. It now seems that there may need never have been such a singularity. Bludman, Alan Guth (MIT), Demosthenes Kazanas (GSFC), and Szalay all discussed aspects of an early universe in which, as a result of symmetry breaking, there is a phase transition in which particles are made at the expense of condensate energy. Such a model has non-zero cosmological constant initially and several advantages over the standard model. It may explain why Ω_0 is close to one and why there are no magnetic monopoles. In addition, its pre-hadron phase violates the positivity condition that is assumed in the trapped-surface argument from which Roger Penrose (Oxford Univ.), Stephen Hawking (Cambridge Univ.), George Ellis (Univ. Cape Town), and others have concluded that there must be a singularity in our past. That is, the universe could have begun as an Einstein static model which then expanded exponentially with time and was transformed into a Friedman solution during the phase transition. The exponential expansion phase allows regions of the universe that would otherwise have been outside each other's horizons to communicate, thus, perhaps, accounting for large-scale homogeneity and isotropy.

On smaller scales, there must always have been lumps in the mass distribution (or galaxies and people could never have come into being). Discussions of galaxy formation normally consider both isothermal and adiabatic fluctuations in the early universe as possible precursors. But primordial isothermal fluctuations in a standard model won't work if neutrinos dominate the mass density, as the neutrino/photon ratio is a unique function of temperature (for high temperatures). Adiabatic perturbations remain a possibility, though they lead to the largest scales collapsing first, so that clusters form before galaxies, at a redshift near three, and in a way that may already violate existing limits on microwave and X-ray background fluctuations. Either adiabatic or isothermal perturbations will work if they can be produced after neutrinos are no longer in thermal equilibrium with the photons. J. P. Ostriker (Princeton Univ.) proposed a model of this sort, in which winds from a very small number of randomly arising galaxies make shocks in the surrounding gas, which then collapses to make additional galaxies. This is analogous to supernova-induced star formation which probably occurs in some regions of the Milky Way disc. The model appears to account naturally for the average mass scales of galaxies and rich clusters. The latter is simply the largest shock that can cool and so collapse in a Hubble time.

Relativistic astrophysics is, as we said before, whatever looks interesting in alternate Decembers. Three recent calculations, pertaining to galaxy evolution and presented in the form of films, were good illustrations of this principle. J. Richard Gott (Princeton Univ.) and Richard Miller (Univ. Chicago) and their respective colleagues have shown cinematographically that a random distribution of point masses (galaxies) in an expanding universe will interact gravitationally in a Hubble time to produce quite plausible-looking clusters. Miller has also followed on film the evolution of two disc galaxies, surrounded by massive halos, as they collide and merge. The product is, he says, not an elliptical galaxy. Finally, Philip Seiden (IBM Research Center) has mimicked a wide range of observed spiral galaxies by allowing star formation, initiated at random, to propagate through a differentially rotating gas disc. There are five free parameters, but each corresponds to a physical property that varies among real galaxies. And his movies could almost be time lapse photographs of the real thing.

ACTIVE GALAXIES AND CLUSTERS

All galaxies are presumably "active" at some level, even ours. Most notably, Allan Jacobson (Jet Propulsion Laboratory) reported that the flux of positron-annihilation gamma rays reaching us from the source in the direction of the galactic center declined by a factor of three or more between fall 1979 and spring 1980, implying a source size of less than a parsec. The 1979 power in the line (and thus the positron production rate required to make it) was about 10^{38} ergs/sec. Several models are possible. At least two other lines (at 4.4 and 1–2 MeV) have been reported by some observers and not others in the same source. They too may come and go. The HEAO-3 high resolution gamma ray spectrometer that saw the positron line in 1979 is no longer working. But David Gilman (NASA Headquarters) anticipates that a NASA-sponsored balloon flight from Australia will permit a new search in fall, 1981.

A coffee-break rumor of variability on a similar time scale (months) in the very compact galactic center radio source (Sgr A West) will probably have been definitely confirmed or denied by the time you read this.

Finally, the dynamics of about 15 small (~ 1 $M_\odot$) gas clouds, orbiting very near the galactic center, indicates that they are moving in the gravitational potential of several million solar masses, confined within less than 1 pc. The best fitting model, as discussed by Jan Oort (Sterrewacht, Leiden), includes both a dense star cluster and a point mass (black hole), each of about 3×10^6 $M_\odot$. The clouds are seen via their NeII infrared line emission and may be envelopes stripped from red giants by collisions in the dense star cluster. The clouds have rather short lifetimes; one should be swallowed by the central object every thousand years or so, providing enough accretion luminosity to keep the remaining ones ionized and, presumably, to power assorted other galactic center phenomena.

On a much more vigorous scale of activity than occurs in the Milky Way, the X-ray quasar NRAO 140, analyzed by Alan Marscher (UC San Diego) and John Broderick (Virginia Polytechnic) displays variability that can only be accounted for on the basis of relativistically expanding ($\gamma \gtrsim 4$), material no matter what our distance from the source. Similar relativistic motions (assuming redshift distances) show up in VLBI radio maps and, are normally expansions. Maps of 3C 84 and 3C 390.3, compiled by Eugen Preuss (Max Planck Inst. Radio Astronomy), on the other hand, show rapid structural changes without systematic expansions.

A little further out from the central powerhouse, X-ray jets a few minutes long appear on Einstein Observatory pictures of two classic active galaxies, M 87 and Cen A. They share alignments with other features in the sources. Radio jets are much commoner and display a wide range of morphologies (somewhat correlated with total radio power). Ed Fomalont (NRAO) suggests that the jet shapes seen in VLA maps of 3C 449 and 3C 326 are evidence, respectively, for a galaxy (or its central black hole) in a binary orbit and for precession of the central power source. How fast is material in the jets flowing out? Most models and many of the observations suggest relativistic speeds; but recent optical spectroscopy of the region of the radio jet in Coma A shows gas at moderate temperature and ionization flowing out along two directions from the center at only a couple of hundred km/sec. It is not clear whether this gas is actually part of the jet or some sort of sheath, which might be moving more slowly than the jet core.

Still further out from the active center ought to be some sort of galaxy. Spectra of the fuzz surrounding the nuclei of 3C 273 and the BL Lac object 1218 + 304, taken by Susan Wyckoff (Arizona State) and Donna Weistrop (GSFC) respectively, show continuum colors like those of elliptical galaxies. The 3C 273 spectrum also has several emission lines at the same redshift as the qso lines, but representing gas under conditions characteristic of galaxies.

The much-publicized double and triple qso's (Ref. 6) seem to have two relativistic phenomena going on: whatever makes a qso in the first place, plus whatever gravitational lens (presumably an intervening galaxy) makes the multiple images. The two main radio components of the double quasar, 0957 + 561, show the same polarization, according to Fomalont, though only one has a jet. This is explicable either in terms of variability of the jet or in terms of the details of the lens image formation process. Gravitational lenses as a way of enhancing qso brightness and variability were first suggested more than a decade ago by Jeno and Madeleine Barnothy. Recent detailed models include the effects of the radial distribution of mass in the lensing galaxy or cluster, and, according to James Gunn (Princeton Univ.), can provide good matches to the brightnesses and positions of the components of both 0957 + 561 and the triple qso, PG 1115 + 08. Tests of the models should eventually be possible because they predict structure associated with individual stars in the lensing galaxy and definite time delays between variations of the several components.

We have mentioned only a few bright patches on the crazy-quilt of active galaxy observations. No one model can possibly deal with it all at once; but the theorists are in there fighting. The current "best buy" scheme, as outlined by Martin Rees (Cambridge Univ.), has the center of a normal galaxy evolving to a supermassive black hole quite early in the galaxy's life. Accretion onto the black hole is then the basic energy source. The accreting gas forms a disc, whose geometry (with or without the help of magnetic fields) tends to collimate gas, blown out by radiation pressure, into two oppositely directed jets, formed either near the Schwarzschild radius or about 1 pc out (twin exhaust model). Within these models, what sort of activity we will see depends on the accretion rate (rates larger than the Eddington limit giving rise to qso's and lower ones to things like M 87), on how the jets are oriented (ones roughly in the plane of the sky yielding classic, extended double radio sources and ones pointing almost at us making the more erratic varibility of BL Lac objects and OVV quasars), and, undoubtedly, on other things not yet included in the model.

Problems remain. For instance, if the jets are to be made of ordinary hydrogen, the protons must acquire far more than their fair share of the accretion energy for the gas to have adequate bulk velocity. But an electron-positron gas is awkward too, as the pairs tend to annihilate before they can get out of the central power-source region. Several stages of energy transfer among particles, bulk motion, and gamma rays may be needed to get the energy out into the jets and blobs that we see.

The most relativistic phenomenon associated with clusters of galaxies is the emission of X-rays by hot gas trapped in the cluster potential well. Given the Einstein Observatory, it is much easier to measure the intensity and spectrum (temperature) of X-rays as a function of position in a cluster than to measure velocities for a great many individual galaxies. Thus, according to Riccardo Giacconi (Center for Astrophysics), dynamics of clusters is most conveniently studied by satellite; and the several different types of X-ray cluster morphology seen probably represent an evolutionary sequence. Abell 1367, for instance, shows a number of point sources, some centered on galaxies and some not, apparently indicating ram-pressure stripping in progress. Clusters like this typically have many spirals, low velocity dispersion, and low X-ray temperature. Such relatively unevolved clusters are about 70% of those seen as X-ray sources. At the other extreme are highly evolved clusters with few spirals, high velocity dispersions and X-ray temperatures, and X-ray emission from the entire cluster volume, in a core-halo structure often centered on an optical cD galaxy. A few intermediate cases show two or a few X-ray cores, whose lifetime to fall together is about 10^9 years.

COMPACT OBJECTS

Collapse of stars to compact configurations must certainly occur, or where do all those pulsars (and black holes?) come from. The energies available are enormous: 10^{53} ergs from the gravitational potential energy of 1 $M_\odot$ collapsing to 10 km, and 10^{51} ergs (enough for most supernovae) from nuclear sources alone when 1 $M_\odot$ of C and O burns to iron-peak elements, even if no collapse occurs. But just how the energy is released and transferred to the outer layers of the star so as to heat and blow them off, making the supernova event we see, is not at all clear. Hans Bethe (Cornell Univ.) and Stan Woosley (UC Santa Cruz) reviewed recent progress on these problems for the cases of evolved massive stars (making Type II supernovae) and white dwarfs in close binaries (making Type I supernovae), respectively. In the massive stars, neutronization occurs much more slowly than has previously been thought, because neutrinos get trapped in the core. In one interesting case, core bounce put 6×10^{51} ergs into an outgoing shock, leaving 1.5 $M_\odot$ inside the shock, a convenient mass for a pulsar. In the white dwarf binary case, most of the ~1 $M_\odot$ that burns must be blown out in order for radioactive decay of Ni^{56} (the dominant product nucleus) to Fe^{56} to produce the observed light curves. One supernova of this type per 50 years would, over 10^{10} years, just make all the iron we see in the galaxy. The explosive burning has the additional virtue of making appreciable Ca^{44}, one of the few nuclides not easily accounted for in the standard scheme of nucleosynthesis.

How often does all this happen? That may be hard to tell if the events don't all look the same or leave the same sorts of remnants, but Richard Manchester (CSIRO) has revised the galactic pulsar birth rate down to one per 150–200 years (with fan beaming of the pulsar radiation) or one per 30–40 years (with pencil beaming). These are reasonable matches to Gustav Tammann's (Basel) supernova rate (one per 20–30 years) and Graham Smith's (Jodrell Bank) supernova remnant formation rate (one per 80 years). Possible progenitor masses that would yield pulsars at the right rate include 4–5.5, 5–9, and 7–∞ $M_\odot$.

Once a compact object has formed, we ought to be able to see it. Absence of radio emission from extragalactic supernovae and of unpulsed X-ray emission from galactic neutron stars has, therefore, been worrisome. Both have now been seen. SN 1979c (seen in M 100 in April) turned up as a 5 mJy source in April 1980 on a 6 cm VLA map compiled by Kurt Weiler (NSF) and others. It has become visible at progressively longer wavelengths since and could plausibly be driven by a pulsar with $P \lesssim 10$ msec. The October 1980 supernova in NGC 6946 was first detected 37 days after the optical event and increased markedly in flux over the next month. Both these (and the one previous similar detection, SN 1970g) were Type II events.

In the X-ray band, Dave Helfand (Columbia), Gordon Garmire (Pennsylvania State), and Ian Tuohy (Australian National University) have found non-pulsed, point-source emission from the Crab and Vela pulsars, PSR 0355 ($P = 0.156$ sec), the old pulsar 1055-52, and the center of the supernova remnant RCW 103. In the first three cases, it is not clear that the emission is thermal, as there are associated non-thermal, extended sources. In the latter two cases, we cannot be sure of the length of time over which the neutron stars have cooled without heat input. Thus, the meaning of the observations remains ambiguous, given that many other pulsars and supernova remnants yield only upper limits. Particularly striking is SN 1006, for which an upper limit of 8×10^5 K can be set to the temperature of a remnant neutron star. The observed fluxes and upper limits are not, according to David Pines (Univ. Illinois), inconsistent with thermal emission from neutron stars cooling in accord with the best recent calculations. The competing school of thought (*e.g.* Sachiko Tsuruta, Univ. Montana) was not represented at the symposium.

Neutron stars in binaries appear to be responsible for most of the relatively constant galactic X-ray sources. Some interesting recent observations are (1) Vela X-1, monitored with Hakucho by Minoru Oda (Univ. Tokyo) shows spin-up and spin-down events correlated with its X-ray flares; (2) 1823-371, recently identified as a binary by Keith Mason (UC Berkeley) displays an unprecedented partial eclipse, implying a very luminous cloud around the compact object; (3) the spectrum of Sco X-1, analyzed by Nick White (GSFC), requires a two-component fit, with X-rays apparently coming from both the inner edge of an accretion disc and a hot corona around it; and (4) four of the 18 pulsating sources studied by Joachim Trumper (Max Planck Inst. Extraterrestrial Physics) show cyclotron lines, implying surface magnetic fields near 2×10^{12} gauss.

On the theoretical side, there is still no self-consistent model of accretion onto neutron stars that includes all the important gas and magnetic field effects, though the theorists again are in there fighting. Silvio Bonazzola (Meudon) and Peter Mészáros (GSFC), for instance, find it possible to reproduce observed beaming patterns reasonably well.

Two of the compact, somewhat variable, presumably binary X-ray sources, Sco X-1 and SS 433, deserve a paragraph of their own. Barry Geldzahler's (MIT) VLA maps of Sco X-1 continue to show a component coincident with the optical object, and two outlying blobs whose spectra and polarization are much like those of the hot spots at the tips of extragalactic double radio source components. Sco X-1 is, perhaps, a scaled-down version of an active galactic nucleus in which accretion occurs at less than the Eddington rate. The local version of super-Eddington accretion, according to Rees, is SS 433. Progress in understanding this object since the 1978 Texas symposium (when all we could really say is that it was both coming and going) has been enormous, according to Bruce Margon (Univ. Washington). Two well-defined periods have been found, at about 13 days (a binary orbit, according to David Crampton and its other discoverers at Dominion Astrophysical Observatory) and 164 days (apparently the precession of a massive disc and associated relativistic jets). A tentative report that the latter period is decreasing at a rate of about 20 minutes a day ($\Delta P/P \sim 2 \times 10^{-3}$) seems to have been a false alarm.

Although the emission line velocities, which define the 164 day period, are approximately fit by a sine wave around gas speeds of ±0.26c, there are deviations of up to 10,000 km/sec which repeat from cycle to cycle (about 6 cycles had been observed as of December 1980) and non-repeating deviations of up to 800 km/sec. Polarization varies in phase with the velocities, indicating it is intrinsic to the source.

Last, and probably most important, a series of 6 cm VLA maps made by Robert Hjellming (NRAO) and Ken Johnston (NRL) show complex structure and motions at a rate of about 3″/yr. This translates into 0.26c at a plausible distance of 5.5 kpc. In addition, many of the structural details are well-matched by a sort of cork screw of emission travelling out from the center at this speed and turning with the 164 day period. This comes very close to being direct evidence of energy flowing out in high-speed jets from a central power supply and strengthens the arguments for a connection between SS 433 and the surrounding supernova-remnant-like object, W 50.

Reasonably steady gamma ray sources also exist. Boudewijan Swanenburg (Huygens Lab, Leiden) reported that, of 25 seen so far by Cos B, only 4 are identified (the Crab Nebula, Vela, 3C 273, and the Orion molecular cloud). At least two of the unidentified sources are variable, implying sizes considerably smaller than the 2° resolution of the observations. The flux in radio, optical, and X-ray photons must be less than 10% of the gamma ray flux for all of them. The distribution in galactic coordinates yields an approximate distance scale, implying powers of order 10^{36} ergs/sec. There are no very convincing models; thus including these sources in our compact object section is a sort of prediction.

More violent variability occurs among the X- and γ-ray bursters. The former have been plausibly modeled for several years as explosive helium burning on accreting neutron stars (with accretion luminosity perhaps being responsible for the special case of the rapid burster as well as for the steady emission of the others). Sufficiently high accretion rates should yield steady burning. Thus it is encouraging that some bursters turn off when their steady X-ray luminosity is highest. In addition, a burst has been seen from the transient source Aquila X-1, known to have a G2-K5 companion, adding to the evidence for a binary model. Oda, however, reported several Hachuko Satellite observations that are difficult to interpret within the model. Some sources show an uncomfortably low and/or widely variable ratio of steady-to-burst luminosity. This, according to the model, ought to be constant at 100 (the ratio of gravitational potential to nuclear energy available from accreting gas). And about four cases are now known of pairs of bursts separated by only about 10 minutes, far too short an interval for a new fuel supply to accrete. Apparently second-generation models will have to include explosive hydrogen burning or some other fuel reservoir than can be tapped on and off.

Gamma ray bursters, on the other hand, have rather suddenly come to seem much more comprehensible than they were. Although there are still no proper optical, radio, or X-ray identifications, the strongest burst to date (5 March 1979) came from a direction inside, though well off the center of, N 49, a Large Magellanic Cloud SNR; and archival Los Alamos data show delayed X-ray emission several minutes after some bursts. The March 5 event was followed by three less powerful bursts; at least one other gamma burster has recurred (B1900 + 14, 1979 March 24, 25, and 27) but without a very bright initial event being seen. Most suggestive of all, a number of gamma ray bursts recorded by Venera 11 and 12 and analyzed by E. P. Mazets (Acad. of Science, Leningrad) show spectral lines of two kinds: (1) cyclotron lines indicating magnetic fields near the 10^{12} gauss characteristic of neutron stars (a Goddard Solar Maximum Mission spectrum of one of these shows that the feature varied through the burst), and (2) a line at 400-450 keV, which is apparently the positron annihilation line, redshifted by the amount you would expect from the surface of a neutron star. Several events showed other lines which, if correctly attributed to iron and other common elements, also imply redshifts near 25%. Richard Lingenfelter (UC San Diego) accounted for lines in the spectrum of the unusually long burst of 10 June 1974 this way as far back as 1978; the redshifted 847 keV Fe line was identified in more recent events by Bonnor Teegarden and Tom Cline (GSFC) using their ISEE-3 instrument. The number of gamma ray bursts vs. flux implies that the sources are confined to the galactic plane at an average distance of only about 200 pc. Thus they must be relatively common and not optically conspicuous. Both points imply either low-mass binaries or single stars. The distance scale and the number of events we see yields a total galactic rate of 2×10^4 per year, so bursts must recur, no matter what the sources are. A typical burst luminosity is 5×10^{38} ergs (and 10^{42} ergs for the 5 March event at the LMC distance).

Given all this, recent theoretical work has inevitably focussed on explosive events in neutron stars. There are two main classes of model. Reuven Ramaty (GSFC) has considered what happens when an interior glitch releases up to 10^{46} ergs inside a neutron star. Oscillations deposit a small fraction of the energy in the NS magnetosphere as fast-moving particles, which make $e^{\pm}$ pairs. The pairs, being magnetically confined to a small volume, cool and annihilate quickly, producing the observed phenomena. Because of the large energy involved, this model is particularly relevant to the 5 March event.

Stirling Colgate (Los Alamos National Lab), Woosley, and others have considered another class of model in which the event is initiated from outside. Material falls on to the neutron star (in the form of gas from a companion, from the general interstellar medium, or even from an asteroid or comet hitting the surface) and nuclear burning occurs explosively. The chief difference from the X-ray burst case is that the very strong magnetic field confines the plasma to high temperature and density, so that cooling occurs rapidly and mostly via hard photons. It will probably be some time before we know which sort of model is most applicable, or even whether all the events are really the same sort of thing.

ACKNOWLEDGMENTS

Our very special thanks go to the Founding Fathers, Ivor Robinson, Alfred Schild, and Engelbert Schucking, without whom the phrase relativistic astrophysics would still not mean anything. In addition, both our thanks and our apologies to all those of our colleagues whose results we have used and misused, failed to credit, or credited to the wrong person. There were more than 700 people at 10th "Texas," every one of whom contributed something important, although we have not mentioned all their names.

REFERENCES

The proceedings of the 10th Texas Symposium on Relativistic Astrophysics will appear as a volume of the Annals NY Acad. Sci., edited by R. Ramaty and F. Jones. Most of the people mentioned in this report were speakers at the symposium, and their own versions of their remarks, with references, will appear in the proceedings.

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