SUMMARY

JOHN ARCHIBALD WHEELER
Joseph Henry Laboratories, Princeton University, U.S.A.

Report what you agree on. Report what you disagree about. Report what should be done to settle the disagreement. These are the famous three instructions of the august patron of several pathbreaking conferences held in Rome. The present symposium is no less historic. However, it is not possible to work out here a similar agreed-upon statement. With 140 of us present, our richly charged symposium is too large for us to undertake that task, and the time available is too short. Also, to our regret, Dennis Sciama could not be here to give us his summary and his answers to the famous three questions. Therefore, in undertaking this review in his place, I can only offer one man's personal perspective.

1. The Symposium in One Sentence

When someone asks us to state the most important result of the symposium in a single sentence, it is difficult to do better than quote the words of our colleague, R. Giacconi, September 7: 'We now have strong evidence in favor of Cyg X-1 being a black hole.'

2. The Search for Black Holes, Neutron Stars, and Gravitational Waves; and Further Predictions about Black Hole Physics

When we are asked for a slightly fuller but still broad brush review, we cannot escape four major points. First, black holes would be beyond our grasp if it were not for the advent of X-ray astronomy. The identification of Cyg X-1 as a black hole is based on the identification of an X-ray and an optical source; on its mass (which in turn depends upon the recent determination of its distance as 2.5 kpc or more); on its compact character; and finally, as especially stressed in the discussions of this morning, on the irregular variations of the Cyg X-1 X-ray intensity on a fractional-second time scale. X-ray astronomy and general relativity have become partners in the investigation of black holes and neutron stars.

Impressive though the evidence is that Cyg X-1 is a black hole, we recall occasions out of the history of physics when what seemed like a discovery turned out to be a mistake. Therefore we are fortunate that there are a few colleagues here and there around the world who look for rival explanations for the observations. No such proposal has been put forward at this meeting; and none of which I have ever heard now remains viable; but not until all such tests have been met and passed will we be able to rank the black hole character of Cyg X-1 as a battle-tested truth.

C. DeWitt-Morette (ed.), Gravitational Radiation and Gravitational Collapse, 217–223. All Rights Reserved.

Second, thanks to X-ray astronomy, neutron stars have shown up for the first time that are married to normal stars in binary systems. As a consequence means are becoming available to determine the mass of an individual neutron star in the married state, as we never could for a neutron star in isolation. Our discussions here make us very mindful of the prospect to obtain in this way masses for so many neutron stars that the critical mass cut-off will stand out, as it did in earlier times for white dwarfs. Then we will have a unique criterion of new precision to distinguish, among compact objects, between neutron stars, below the critical mass, and black holes, above it.

Third, disagreement continues whether any real gravitational waves have yet been detected, but the long term prospects for gravitational-wave astronomy look brighter than ever.

Fourth and last in this broad brush review, theoretical investigations reported here give us more detail than ever on the properties of black holes. We have long known three ways to probe black holes: the pulse of gravitational radiation given out at the time of formation; X-rays given off when matter accretes onto a black hole after its formation; and 'activity', from energy given to its surroundings by a rotating black hole. Little new came out here about the pulse of gravitational radiation at the time of formation. Much was reported that is new and of great interest about accretion. Several most interesting and beautiful aspects of 'activity' were treated. However, we are still some distance from a comprehensive picture of what can happen and what will happen when matter, fields and plasma interact with a 'live' or spinning black hole.

3. The Scope of This Review

Turn now to a more detailed review. Recognize at once that several of the reports presented at this conference were already in themselves excellent reviews. It would be out of place to try to summarize these summaries. Also there were many interesting contributions, so independent and original that they do not fit into any simple pattern. They ranged over topics from the new method of Newman to get solutions of Einstein's equations, and the new solution of Plebanski, both making use of the magic of complex numbers, to the work of Sejnowski on gravitational radiation reaction and absorption, at last making clear the question to which the Bel-Robinson tensor is the answer, and to the report of Grischuk on gravitational radiation of cosmological origin, and to many another fascinating topic, but all together they make a fare too rich to summarize here. If this is agreed, it may be permissible to limit this review to these five topics: sources of gravitational radiation, detectors of gravitational radiation, collapse, X-ray observations, and accretion.

4. Sources of Gravitational Radiation

Sources of gravitational radiation in the early Universe have been imagined, but no

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such primordial radiation has been conceived so far which is not so attenuated by the expansion of the Universe as to be unobservable.

The thermal gravitational radiation produced in the primordial cosmic fireball should today have the same order of magnitude of energy content as the relict electromagnetic radiation. Moreover, the precise ratio of the two depends in an astrophysically interesting way on the times of decoupling of matter from the two forms of radiation. However, even the most ambitious detector of gravitational radiation ever conceived falls short by many powers of ten of the sensitivity required to determine this ratio.

Ya. B. Zel'dovich has directed our attention afresh to 'fly-by' gravitational radiation, when the two speeding stars are compact, and Nutku and Matzner have an interesting new way to calculate the intensity of this radiation when the velocities are relativistic. Non-relativistic velocities are to be expected in the case of greatest astrophysical interest, the case treated some time ago by Sanders and Spitzer and others, a galactic nucleus that evolves to ever greater compaction. Neutron stars and white dwarfs collide, gas is driven off, and from that gas new stars form still closer to the center. A catastrophe comes closer each day that passes. No one sees any outcome possible but the formation of a giant black hole, a 'nimmer-satt' in the words of Regge. The object grows and grows by accretion of stars. Its mass rises decade by decade, $10\ M_\odot$, $10^2\ M_\odot$, $10^3\ M_\odot, \ldots, 10^6\ M_\odot, \ldots$. Ultimately it depletes its surroundings. It settles down to a slow terminal stage of growth. Its mass nearly stabilizes at a value that may range anywhere from $10^6\ M_\odot$ to $10^9\ M_\odot$ depending on the mass and compactness of the original galactic nucleus. As Ya. B. Zel'dovich has emphasized, the pulses of gravitational radiation given out in encounters and near encounters between compact star and compact star in the Sanders-Spitzer regime have a frequency spectrum that eludes detection by any of the detectors now in action. Moreover we do not know at what stage the nucleus of our own Galaxy is in the process of building a black hole. Is that process far in the future? Or is it far in the past? Or by some fortunate accident are we in the midst of it today? We know as yet too little on this score to count it as anything but a gamble to build a detector specially designed to respond to these low frequency pulses. When the velocity of fly-by rises from nonrelativistic values to relativistic values we have in the considerations of Matzner and Nutku a new way to estimate the shape and intensity of the spectrum of splash radiation.

Quite another source of low frequency gravitational radiation, waves rather than pulses, was not considered in detail because of shortage of time: the very close binary systems that have received detailed analysis in recent times by Faulkner and Paczynski.

Supernovae, and events like supernovae, have been and remain the potential sources of excitation of a Weber bar of the greatest current interest. Events of this kind, the recent review by Press and Thorne makes clear, should be picked up once a month or so from nearby galaxies with the kind of Weber-bar detector one can hope to see in some years' time. However, it is clear from the discussions in this

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meeting that we are far from any detailed hydrodynamic analysis of the absolutely central feature of such sources, the time history of the sudden changes in quadrupole moment that take place during this collapse. The greatest variety of scenarios has to be envisaged. The scenario depends upon the mass and angular momentum of the white dwarf core that eventually becomes unstable in the course of its normal astrophysical evolution. Endowed with even a modest initial angular velocity, this core after collapse will be rotating very rapidly. It is natural to think of the collapsed system having under some circumstances the form of a pancake, of neutron matter, which ultimately fragments into two or more neutron stars. One can envisage a so-called 'pursuit and plunge' scenario when initial mass and angular momentum are right. It is natural to believe that there will be the greatest variety of scenarios depending upon the initial mass and angular momentum. Arnett has pointed out to us here some considerations suggesting that the original white dwarf core may never have a mass in excess of 1.4 $M_{\odot}$. If confirmed, this consideration will be a helpful limitation on the number of cases to be considered. Apart from considerations by Hawking and Gibbons on the minimum number of zeros in the Riemannian curvature of the emitted wave, regarded as a function of time, one knows almost nothing about the details of the shape of the pulse that will be produced in any one of these scenarios. Here is one of the greatest gaps still remaining to be filled if gravitational wave astronomy is to become a useful tool for diagnosing supernova events.

5. Detectors of Gravitational Radiation

Tyson emphasized that detectors of gravitational waves would not exist, or would be rudimentary, if it were not for the pioneering work of Joseph Weber, which he warmly praised. He also pointed out that the detectors attached to a typical Weber bar have improved in sensitivity by two orders of magnitude since Weber's 1970 work; or otherwise stated, the noise level achievable today is two orders of magnitude less than what Weber had to contend with in 1970. He noted that neither Drever nor the Frascati group nor the Munich group nor Braginsky nor the Paris group see anything like what Weber reported in 1969. Either the effect has decreased from then to now by a factor of 100 or more; or Weber's equipment responds to events to which the equipment of others does not respond; or the computer program used to analyze the tapes is at fault; or some other explanation has to be found. The Rochester-Bell Laboratory coincidences with zero time offset between the two tapes show for events of magnitude $\frac{1}{2}kT$ no evidence for anything with a frequency anything like five per day. Garwin's impressive upper limit on the number of gravitational wave pulses, not discussed in detail, increases the evidence reported by these other groups. Fortunately for the future of the subject several of the experimental groups are active in providing other groups with copies of their tapes so that intercomparisons can be made, in the best traditions of experimental physics. One can hope that in a matter of not too many months the numerous experimental groups now at work will be able to give a definitive assessment of 'gravitational radiation' at 1600 cycles.

No one could fail to rejoice at the marvelous new increase in sensitivity of gravitational wave detectors being pioneered by Fairbank at Stanford, Hamilton at Baton Rouge, and the Rome group. When this equipment reaches its ultimate sensitivity, gravitational wave astronomy should be fully established.

Zel'dovich, building on pioneering work of Gerstenstein, Bacalette, de Sabbata, Fortini, Gualdi, Westervelt, Kopvilam and Nagobaroi, described how the gravitational wave travelling in a magnetic field gets converted into an electromagnetic wave, and how a resonant cavity provides such 'conversion' at a great saving on power as compared to free space; went on to point out the impracticability of such a converter under any conditions envisaged to date; but remarked that some new idea may yet be discovered which will make such a converter useful.

Reference was also made in the course of the meeting to the concept of Ruffini, that a charged black hole (if such exists) automatically provides a device to convert incoming gravitational waves to outgoing electromagnetic waves.

6. Collapse

Chandrasekhar presented a systematic review of methods for analyzing the stability of stellar systems, and broadened the methods available for treating the onset of collapse. He noted the special problems which arise in some of these methods in analyzing the stability of the Kerr geometry.

Penrose brought together two ideas that one previously has usually analyzed in disjunction. One is the singularity encountered in models of the Universe itself in the final stages of its gravitational collapse and also at the time of the big bang. The other is the singularity associated with a black hole. He showed how these two apparently different kinds of singularity can be regarded in union. He also pointed out that the concept of 'absolute event horizon' depends on a distinction between world lines which have finite and infinite life. However, no such sharp distinction can be made in a closed Universe of finite volume and finite life. Nevertheless the concept of event horizon under everyday circumstances keeps much of its usefulness. Among topics needing further investigation and elucidation Penrose listed these: (1) Can one assume stationarity (of Newman-Penrose 'constants') for a Kerr black hole? (2) What happens to it when it is subjected to perturbations comparable to the difference $(m-a)$? (3) Can the horizon grow into a singularity?

Zel'dovich pointed out objections to the concept of 'white hole', especially the unrealism of thinking that such an object could remain 'hidden' for a long time and then suddenly erupt. In contrast, even if such objects were allowed, he emphasized, they would have exploded in the very earliest days of the Universe.

These considerations on the inequivalence of past and future in black hole physics remind us of the role of the arrow of time in other parts of physics: in statistical mechanics, in biology, in the force of radiative reaction, in the distinction between retarded and advanced potentials and in cosmology itself. For a closed universe which expands, reaches a maximum content and recontracts, the question has often been raised whether with the 'turning of the tide' the sign of the rate of change of entropy with dynamic time will also change. It is difficult to cite an issue on which there exists today a greater diversity of views. A black hole is an object of very special interest in this connection because in its collapse and in its response to perturbations the one-sidedness in time, the 'friction' that goes with irreversibility plays percentage-wise a larger role than it does in any largescale dynamic process that one can easily name. Surely new insights await us on the connection between the arrow of time and cosmology.

Thanks to Teukolsky we have seen another of the miracles of mathematical physics in the separation of the wave equation for electromagnetic and gravitational waves in the field of force of a Kerr black hole. He, Press, Starobinski and Hartle have told us of the fascinating conclusions they can draw in this way about the interaction of a rotating black hole with its environment. Some of these effects, as for example the ability of a black hole to send out an electromagnetic wave with more energy than the arriving wave (superradiance) are too new for all their astrophysical consequences to have been seen or exploited.

Following Markov's review, 'Global Properties of Black and White Holes', Bardeen summarized the large number of properties of black holes relevant to their observation emphasizing the difficulties of getting black holes with any substantial charge but pointing to the likelihood of black holes with a ratio (angular momentum)/(mass)^2 of the order of 0.95. He pointed out the appearance of a hot blob of radiant matter traveling close to a black hole and shift in spectral lines from it as a tool for studying dynamics in the field of a black hole. He described many of the major features of the accretion disk, a topic of great importance which came up again and again in subsequent sessions of the symposium.

7. Observations

In addition to the evidence on Cyg X-1 presented by Giacconi and Kraft, leading to the conclusion that this object has a mass of 10 solar masses or more and must be a black hole, we heard from Giacconi that there are half a dozen candidates or more for other black holes. Moreover, the chances would appear good that there will be among these objects one or more where the double star system is oriented relative to us in such a way as to give occultation, a piece of good luck not found in Cyg X-1.

Arnett has made us more aware than ever of the hydrodynamic problems of forming a black hole from the precursor star. He points out that the white dwarf core of star models does not exceed approximately 1.4 $M_\odot$. A very much larger mass seems required to produce a black hole of 5 or 10 solar masses. The initial white dwarf core can only hope to reach partway toward this mass requirement if it is endowed with considerable angular momentum, as shown by Ostriker. Therefore a proper hydrodynamic treatment of the collapse of a rotating system would seem necessary if one is to understand how the conditions arise for the creation of a black hole. We have also been reminded in the course of this symposium of other issues of stellar structure and stellar dynamics including not least the fate of a normal star which has ingested a black hole ('cancer of the stomach'). This configuration presents a special case of the general problem of accretion.

8. Accretion

Schwarzmann, speaking for himself and Sunyaev on the search for black holes and the mechanism of luminosity focussed primarily on an isolated black hole in interstellar space, noted that the distinguishing characteristics of the spectrum will be (1) no lines (2) a non-thermal distribution and (3) fluctuations in intensity significant over time intervals as short as 10^{-5} s.

In contrast to the low luminosity of a black hole in interstellar space, a black hole in a double star system will have a much higher luminosity. Schwarzmann suggests a picture for the structure of the accretion disk alternative to that of Bardeen, Pendergast, Rees, Sunyaev, Thorne and others, and reasons that the disk swells, gives way to plasma instability, and breaks into clouds linked by magnetic lines of force. He expects that such a source as Cyg X-1 may be a powerful source of relativistic particles.

9. This Conference and Copernicus

It is difficult to think of any occasion in the history of astrophysics when three stars at once shown more brightly in the sky than our three stars do at this conference today. First is X-ray astronomy. It brings rich information about neutron stars. It begins to speak to us of the first identifiable black hole on the books of science. Second is gravitational-wave astronomy. It has already established upper limits on the flux of gravitational radiation at selected frequencies. At present sensitivity it stands ready to detect the pulses from the next supernova in this galaxy. At the fantastic new levels of sensitivity now being engineered, it promises to pick up signals every few weeks from collapse events in nearby galaxies. Third is black-hole physics. It furnishes the most entrancing applications we have ever seen of Einstein's geometric account of gravitation. It offers for our study, both theoretical and observational, a wealth of fascinating new effects. And it directs our attention more compellingly than ever to the mystery of the final state in gravitational collapse, the greatest challenge in the physics of our generation, and beyond that, to the greatest issue that science has faced in all its history, how the Universe began, and the old question of Leibniz, 'Why is there something rather than nothing?' Surely Copernicus has something to do with those three stars shining in our sky. Surely the spirit of Copernicus will help us with our questions.