for the octahedral cation indicates that larger space is available for it. The nearest C-K distance is 3.2 Å—the distance between the K ion to the nearest C atom is 3.69 Å and the closest K-K distance is 6.17 Å—much larger than in metallic K. Since the K ions occupy all the available sites in a virtually unchanged C_{60} lattice and the Rietveld fit is extremely good, it is a direct proof of the microscopic homogeneity of the material. The presence of two crystallographically different K sites suggests that it may be possible to prepare other stable compounds. The structures of K_6C_{60} and Cs_6C_{60} which are not superconducting have also been determined. These are bcc structures with K ions in distorted tetrahedral positions.[4]

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COMMENTARY

On every occasion in recent years when Chandrasekhar gave formal and informal lectures in Bangalore, he mentioned with gratitude and affection two of his collaborators—Basilis Xanthopoulos and Valeria Ferrari. So when I read of the shocking news of the murder of Xanthopoulos in Crete by terrorists I wrote him a letter of condolence. He then sent me a little piece which was to appear along with the foreword to Volume 6 of his Selected Papers. I wrote to him 'I received the little piece that you had written in remembrance of Basilis Xanthopoulos and I noted with great sorrow the sentence "My association with Basilis is the most binding in all my 60 years of science". I realized then more than ever the incredible loss you have suffered'. I sought his permission to publish his note in Current Science which he gave. I felt that to publish Chandrasekhar's 'In remembrance of Xanthopoulos', without giving Xanthopoulos' foreword will not do full justice to the close association of the two—the teacher and the student. The foreword also gives us an inkling of Chandrasekhar's method of doing research and his attitude to science as seen by a close associate. —*Editor*

In remembrance of Basilis Xanthopoulos

Basilis Xanthopoulos was shot to death in an unspeakable act of violence on the evening of 27 November 1990 while he was giving a seminar lecture on advanced computing to his senior colleagues at the Research Center of the University of Crete (Iraklion, Greece) And so ended, without warning, a life of love and joy, rich in promise.

Basilis and I collaborated on a variety of scientific subjects almost continuously from 1978, when he was a graduate student, to the present. Some of the results of that collaboration are represented in this volume. The enduring personal friendship that emerged is amply present in the warm and generous foreword that Basilis wrote for this volume (and for which I am deeply grateful)

My association with Basilis is the most binding in all my sixty years in science

On the evening of 28 November my wife and I listened on our phonograph to the second and the third movements of the *Eroica* in a renewal of our dedication to a dear departed friend.

S CHANDRASEKHAR

Foreword to Volume 6 of S. Chandrasekhar's *Selected Papers* by Xanthopoulos

S. Chandrasekhar on black holes and gravitational waves· What a story! Forty years after his pioneer investigations, Chandra returned to the study of the dead stars. He had told us back in 1931 that massive stars could not die as ordinary objects, consisting of regular matter, could. Eddington would rebuff the idea as absurd; the scientific community would side mostly with Eddington; and, although the Schwarzschild solution was waiting around for its correct interpretation, the development of black holes would be delayed by a few decades. So, although all the ingredients were there and we did not have to wait too long, it was not until the sixties that we would incorporate black holes into our world view.

Most of the research on the theory of black holes, including the casting of their name, occurred from the early sixties through the middle seventies. There was the discovery of the Kerr solution, the Penrose–Hawking–Geroch singularity theorems, the Penrose extraction of energy, the Teukolsky separation of the perturbation equations, the Christodoulou–Bekenstein–Hawking thermodynamics, and the Isreal–Robinson proof of the uniqueness of the Kerr solution. After 1974, the general interest shifted to 'quantum black holes' and 'everybody' would concentrate on the Hawking radiation and semiclassical methods.

As usual, Chandra was in a phase difference with his contemporaries: a few decades lead in the prediction, with almost a decade's lag in the mathematical analysis of the theory of black holes. Chandra had always been interested in the stability of astrophysical configurations. He had recently completed his investigations of the stability of rotating stars, and was at Caltech when Teukolsky separated the equations for gravitational perturbations. So it seemed natural for Chandra to embark on an investigation of the perturbations of black holes by developing *ab initio* the theory, and eventually putting his benchmark on the field by writing another book. Instead of going through the scientific context of each paper, I will make some general remarks about the entire work.

The initial challenge for Chandra was the numerically established equivalence of the scattering problems for the odd and the even parity perturbations (now referred to as the axial and polar perturbations) of the Schwarzschild solution. So he worked out by himself the metric and the Newman–Penrose perturbations and, through his transformation theory, established analytically the equivalence of the two scattering problems. Next, the Kerr perturbations evolved, step by step, from the 'easy' ones (perturbations of external fields, potential barriers for their scatterings, axisymmetric gravitational perturbations) to the more difficult ones, which culminated in two major papers on the Newman-Penrose gravitational perturbations of the Kerr space-time (papers 10 and 11 in this volume) [Vol. 6]. In the next couple of years these papers were supplemented and rectified by three additional contributions (papers 12, 13 and 18), establishing identities among the Teukolsky functions, completing the solution, and analysing the algebraically special perturbations.

Completeness of the subject was the main motive for Chandra's consideration of the perturbations of the Reissner–Nordstrom black hole. He considered both the metric and the Newman–Penrose perturbations, established the equivalence of the axial and the polar scatterings, and investigated issues such as the decoupling of gravitational and electromagnetic waves and the transformation of one kind of wave to the other in the scattering process.

Actually, completion of the theory was never achieved. Chandra wanted—and he tried hard—to decouple and/or separate the perturbations of the Kerr–Newman black hole. It is well known in the scientific community that he did try and did fail. Since Chandra failed, no one seems willing to give this problem a serious try, and the perturbations of the Kerr–Newman solution have remained an unsolved problem for the dozen years since Chandra gave up. Perhaps, for the sake of science, he should have kept his failure secret. On the other hand, it is very likely that the Kerr–Newman perturbations cannot be separated, and his documented failure will have saved many scientist-years of fruitless effort.

The first two papers on the gravitational perturbations of the Kerr black hole (papers 10 and 11) probably represent the peak of his scientific efforts. The circumstances under which Chandra wrote these papers should perhaps be revealed.

In 1976 Chandra was mainly preoccupied with the gravitational perturbations of the Kerr solution. In addition, while teaching a graduate course in early 1977, he came up with his favoured derivation of the Kerr solution (paper 4). In the spring of 1977, he worked hard preparing three manuscripts—one on the Kerr solution, and two on gravitational perturbations. (He then thought that these were to be the completion of the Kerr perturbations.) It is worth noting the submission dates for these papers 18 April, 2 May and 20 June, all in 1977. During the second week of August, the GRG-8 conference took place in Waterloo, Canada, and there Chandra gave a plenary talk on his recent work. He shared the drive back to Chicago with Gary Horowitz, and disappeared immediately after!

As we discovered later, in the early spring of 1977 Chandra (who had suffered a heart attack in late 1974) learned that he had a serious heart problem that most probably would require open heart surgery. But how? The Kerr perturbations were not completely solved; the manuscripts had not yet been prepared; and GRG-8 was only a few months away. To Chandra the answer was obvious: he was not yet ready to submit to the surgery, and made it clear to his doctors that they must wait! In mid-August he entered the hospital, and, although the operation was successful, every conceivable complication described in the medical books did in fact occur. Eventually the doctors made it clear to him that his recovery depended solely upon his will to recover. Now, twelve years later, we have written records of his amazing will: *The Mathematical Theory of Black Holes*, the work on the colliding waves, and the studies of the two black hole solutions. His lecture at the Gibbs Symposium (paper 37) presents Chandra's current views on relativity.

Of all his work on black holes, the separation of the Dirac equation still remains, I believe, closest to Chandra's heart. For instance, it is very pleasing to him that through this work it would later be learned that the Dirac equation can be separated in Minkowski space–time, in prolate spheroidal coordinates, and also that the development of a new theory on the separability of partial differential equations would be initiated. Moreover, the recollection that he actually started and finished the separation in the same evening provides great satisfaction.

Judging it retrospectively and comparing it with his life-long previous scientific work, Chandra would describe his 1974–1981 work on black holes as his best scientific effort: it required much harder work and a great deal more effort than all the previous fields he had investigated. I was quite surprised to hear him say that his efforts on colliding waves were comparable to the effort required by the study of black holes. However, although he came to be very enchanted with the beauty of general relativity, his work on radiative transfer would always occupy a central place in his heart.

The study of black holes meant a sacrifice for Chandra. Being an astrophysicist of the real stars, he would always consider perfect fluid solutions of the field equations. The vacuum Einstein equations became relevant to him only because they were relevant to black holes. This sacrifice revealed to him the geometrical structure and the richness of Einstein's theory. Then it became clear to him that he should consider charged black holes as well; and the very most his astrophysical conscience would tolerate was an electromagnetic field much weaker than the gravitational field. 'Downhill, all the way down' is a favourite expression of his, describing his gradual change in interests: from the stars to black holes, from the fluid configurations to the vacuum space–times and then the electromagnetic ones, and, finally, from the approximate techniques to the exact solutions that were the only means for studying colliding waves. Chandra accepted his downhill slide, and soon became fascinated with the simple exact solutions that describe all sorts of different phenomena in the collisions of plane waves. I can still recall the smile on his face when it was pointed out to him that the real bottom of his slide was the paper on the two black holes attached to strings (paper 33), where the charges of the black holes are actually larger than their masses (but no naked singularities occur). What good fortune to ride with Chandra on his slide downhill!

It could be said that Chandra's work on black holes was one of his scientific objectives. Having predicted them from astrophysical considerations before anybody else, he had been learning relativity all these years. And gradually, from the post-Newtonian approximations to the stability of rotating stars, it was natural for him to move on to the perturbations of black holes. In fact it was his interest (in the sixties) in the ellipsoidal figures of equilibrium, and his determination that this theory of Riemann, Jacobi, MacLaurin, and Dedekind should be completed and presented in a unified treatment, that postponed for several years his entry into the realm of relativistic black holes. The work was done from 1974 to 1980, culminating in the writing of his book in 1980–81.

Contrary to the work on single black holes, there were no blueprints for Chandra's work on colliding waves and on two black holes. These papers were not supposed to have existed or to have been included in this volume. Before explaining how they came into being, let me mention a discourse that took place in Thessaloniki in 1981, while Chandra was finishing his book. According to Chandra:

> When I was eighteen, back in India, I had submitted a paper to the Royal Society in London. The foreign mail would arrive in the central post office every Saturday, but it would not be delivered until the following week. So, every Saturday, I would ride my bike for about six miles to the post office, in order to check whether the answer from the Royal Society had arrived and to learn whether or not the paper had been accepted. You see, a couple of months ago—and some fifty-odd years later—I was expecting, with equal anxiety, the referree's report from the Royal Society for my latest paper! Well, it's ridiculous to feel the same way fifty years later, when you're in your seventies. You should grow old; you should *live* all the stages of your life. I want to grow old! I should retire from science after I finish my book.

Well, Chandra managed to grow a little bit—but not much—older, in the intervening eight years. In 1983, after he finished his book on black holes, the gravitational waves began colliding. They were coupled with electrodynamic and hydrodynamic waves in 1984 and 1985. They developed Cauchy horizons in 1986, and they were almost plane waves in 1987 and 1988. Some cylindrical waves appeared, and the number of black holes increased from one to two. The visits to Chicago by his collaborators also increased, and his one-week visits to Rome (one) and Iraklion (four), where he would usually complete the writing of a paper, became more frequent. Therefore, although Chandra obtained the status of Emeritus Professor in 1986 (by terminating an indefinite appointment with the University of Chicago because 'it is better to leave when everybody asks "why are you leaving?" than to stay while everybody wonders "when is this guy thinking of retiring?"'), I do not think he managed to grow much older. During these years he became fascinated with Newton and began translating key propositions from the *Principia* into contemporary mathematical language. His 'Newton's Selected Works' are not included in this collection; they will be the subject of a forthcoming book. So let us proceed with the work on colliding waves.

Two letters from Europe stimulated Chandra's slide to the exact solutions of colliding waves. First was a communication received in the late seventies, from Yavuz Nutku, a former student of Chandra's, informing him that the solution for colliding plane impulsive gravitational waves with nonparallel polarizations is described by the simplest solution of the (X, Y) equations, recently formulated by Chandra (paper 4). The second was a letter from Roger Penrose, dated February 1984, in which Penrose wondered how to describe collisions of impulsive gravitational waves coupled with electromagnetic waves. Since the energy–momentum tensor of the electromagnetic field is quadratic on the field, impulsive electromagnetic waves would carry infinite energy per unit area. Therefore, for the energy to be finite, one would like to demand that the energy-momentum itself should be impulsive (meaning proportional to Dirac's δ-function). But then the electromagnetic field should behave like the square root of the δ-function, and one would be left wondering how to interpret such fields and how general relativity would cope with all of these difficulties.

After his book appeared in print in the spring of 1983, Chandra was thinking about Nutku's letter. He had always wanted to understand the solution describing collisions of plane waves, and that meant that he had to work them out *ab initio*, in his own language. By autumn, he had actually done some preliminary calculations. I recall the day I telephoned him—the day he was awarded the Nobel prize. Before I even had the chance to congratulate him, he shifted the discussion to colliding waves, in which he was quite interested and about which I knew nothing.

In the summer of 1983 Chandra had met Valeria Ferrari in Rome, and had invited her to spend some time in Chicago. In October, Valeria unexpectedly appeared in his office, a telex from Rome never having been delivered to Chandra. This was three days after the announcement from Stockholm. He suggested that they reformulate the problem for colliding waves, to take advantage of the experience obtained with the stationary axisymmetric solutions, and rederive the space–time describing the colliding impulsive waves (the Nutku–Halil solution) in this new formalism. In the next two weeks, and simultaneously with the aftershocks of the award of a Nobel prize, the first paper in the series (paper 19) was almost completed. Later, it would always be referred to by Chandra as 'the Valeria paper'.

Next, Chandra started thinking about the collisions of coupled gravitational and electromagnetic waves. In fact, he actually postponed his departure for Stockholm in order to have a chance to discuss the problem with Penrose, who was then visiting Chicago. This initiated Penrose's letter of February, 1984. The actual work (paper 20) was done in the summer of that year, and it turned out to be more difficult than anticipated.

In addition to the formidable analytical work that was required, it involved, for instance, the conceptual difficulty of accepting a nonflat preinteraction region. But Chandra 'knew' that one had to construct the charged version of the Nutku–Halil solution, in complete mathematical analogy with the Kerr–Newman black hole being the charged version of the Kerr black hole. In the end, it was greatly rewarding to realize that general relativity would overcome the difficulty associated with the squared root of the δ-function, by confining the δ-function singularities only in the Weyl part of the curvature.

The first paper on collisions involving fluids (paper 21) was the most difficult conceptually. Here we had to convince ourselves that we must accept a different equation of state for the fluid in the pre- and the afterinteraction regions. It was also difficult to accept and establish that the collisions of plane gravitational waves may actually lead to the formation of Cauchy horizons (paper 23). We—together with everybody else—were expecting a curvature singularity. It was very surprising when computer evaluations of curvature scalars showed them to remain finite on the surface where they were expected to become singular. It was exceedingly difficult for Chandra to be convinced that something novel and interesting might be happening. However, on my next visit to Chicago, in January 1986, I found that Chandra had actually evaluated the curvature scalars in a very elegant way, with pen and paper, so that they could be verified by ordinary humans. In all our joint work, the only equations that Chandra did not work out by himself are equation 30 of paper 23 and equations 37 and 72 of paper 33.

During the years of the colliding waves, Chandra developed a new habit: He would fly to wherever Penrose happened to be to consult with him *for one day*. Upon his return he would always be very enthusiastic about the successful trip. In fact, in one case (see section 7 of paper 23), he worked out Penrose's suggestions on the return flight, and the problem was solved before he landed at Chicago. Chandra undertook these trips three times—once to Houston (1985) and twice to Oxford (1986, 1988). Penrose's suggestions were always very constructive, and are acknowledged in papers 21, 23, and 26.

1987 and 1988 it became clear that the work on the colliding waves would not be Chandra's last contribution to general relativity. This happened when he began considering cylindrical waves and, later, two black holes. My only regret is that I cannot tell 'a story' for this period—somehow everything proceeded quite fast.

The cylindrical waves were studied in parallel with the late phases of the colliding plane waves. It came naturally for Chandra to investigate cylindrical waves, since they are also described by space–times possessing two space-like Killing fields. The first paper (paper 29) exhibits solutions describing stationary monochromatic cylindrical gravitational waves, possibly coupled with electromagnetic waves. The reader can refer to appendix B of that paper to obtain an idea of Chandra's scholarship. In the second paper with Ferrari, they investigated the dispersion of a cylindrical wave packet that was initially impulsive. They provided a very nice solution, expressed in terms of convergent integrals of divergent functions.

The papers on the two black holes were written, I feel, in an effort by Chandra to fulfill an old interest while disassociating himself from the waves that kept colliding with '...increasing frequency'. He once said, 'If I were younger, I would write a book [on colliding waves],' but certainly he did not want to find himself involved in such a project. The study of the Majumdar–Papapetrou solutions turned out to be very difficult, analytically and conceptually. However, he pursued the problem with a youth's persistence, and after an excruciating analysis he succeeded in describing the scattering of gravitational and electromagnetic waves by two black holes as a six-channel scattering problem. On the other hand, when the two black holes were attached to cosmic strings, the work was completed relatively easily, and no visit to Penrose was ever contemplated. In fact, Chandra was so excited about that solution (paper 33) that he even went so far as to ask the Royal Society whether it would be possible to expedite its publication. And they did!

How does one finish the foreword of the last volume of Chandrasekhar's selected works?

Thank you, Chandra! both personally, and on behalf of science.

BASILIS C. XANTHOPOULOS