Heaven and earth one substance: Bernard Peters and the heavy primaries

Philip Morrison

The material unity of the cosmos has been sought for a long time. One of the strangest forms of matter, the primary cosmic rays, were first shown to be one with the rest of astronomical matter by direct sampling carried out at the top of the atmosphere in 1948 by a young physicist called Bernard Peters along with his friends. The history of the grand question of unity is sketched from Athens up to this day, without technicalities, by an old friend of that pioneer investigator.

The celestial and the earthy

Long ago the cosmologist Anaxagoras came from the east to teach in Athens, before that city had attained its glory. One of his theories proposed that 'the sun was a flaming stone larger than the Peloponnesus'. For such blasphemy he was expelled from Athens, almost 2500 years ago, escaping a capital sentence only through the intercession of the statesman Pericles, whose teacher he had been.

Only around 1450, in his final years, would Copernicus risk open publication of his arguments that the earth was an orbiting satellite of the sun, like the other planets in the sky. Then physicist and astronomer Galileo Galilei, about 1610, recognized with his telescope, the first of all telescopes to succeed in astronomy, that the silvery moon was an earth-like mountainous ball. One of its big central craters was ringed with high rocky peaks, looking very much, he wrote,'like a plain in Bohemia'. He too was punished during those years of religious conflict; the blame directed at him was in part for his explicit unification of the celestial with the merely earthy.

Isaac Newton too would in the 1690s demonstrate an astonishing unity in the world. The sun and the planets danced out their complex steps under the simple rules of gravitation. Within a few decades it was shown that a mountain in Wales could pull aside the surveyor's plumb-bob just as the moon pulled the tides; gravitation was as earthy as it was celestial. Then laboratory instruments were made sensitive enough to detect the tiny gravitational forces from heavy weights right in the lab. By the early decades of the nineteenth century the astronomers had shown that double stars themselves circulated in orbits fully obedient to universal gravitation. Newton's prescriptions extended to regions so distant that they had never been under the sun; Newton's force was universal indeed.

Beginning in the mid-nineteenth century another material unity appeared at the slit of the astronomer's spectroscope. The surfaces of the sun and the stars were chemically analysed by their light, the spectral lines, at first only qualitatively, by now quantitatively as well. The results are profound: all the matter whose form we can see is solid like the moon's craters or gaseous like the solar surface (liquids are rare), and all of it gravitates just as here below. All of it shares a common constitution: with the human hand—your hand—or any common pebble on the beach, celestial matter too is made up entirely of a somewhat varying mix of a hundred more or less familiar earthy atoms. Here below as there above, the recipes of all matter call for no more than that; atoms comprise the entire material world.

The cosmic-ray primaries

By the 1930s the incoming cosmic rays—their very name hints at their story—were demonstrated to be mainly positively charged nuclear particles, the protons. They formed a unique gas out in space, particles moving uniformly in all directions, with speeds relative to earth that were far greater than the speeds of planets, comets, or even stars, close to the ultimate speed, that of light. The cosmic-ray primary particles seemed to be a simple gas, the simplest of stable particles, in uniform isotropic flow at relativistic energies still encountered nowhere else in nature.

Those incoming primaries might well be truly cosmic, for the first time a kind of matter that was distinct from the rest of the astronomical world. Perhaps they were so strangely simple because they were the sign of an earlier, distinct phase of the universe, relics of a physics of creation long past, of some novel, never-repeated processes we could never grasp. The Oxford cosmologist E. A. Milne said so explicitly, 'Once, much later, when I was fortunate enough to talk about the

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matter with elderly Albert Einstein, he too — he easily conceded that he was far from well-informed in that field—still felt that such an exceptional point of view was possible for so remarkable a phenomenon as the cosmic rays'.

Most of us hoped instead for universality. Cosmic rays too might some day be explained as strange samples from our own world of matter; hydrogen stirred into random motion and promoted in energy well beyond the energy of any nuclear decay. They would in effect be familiar matter in a new condition, some kind of 'flaming stone', just as the amazing sun is itself in reality no novel material but is a fiery ball of impure hydrogen, even though it is much larger than the Peloponnesus.

The label *cosmic* seems apt enough for that remarkable unceasing radiant flow from space, even though they are not literally cosmic, but astronomical; we are pretty sure that nearly all the rays are as galactic as the starry sky itself, yet the term sticks. It was in the year 1948 (see ref. 1) that we were shown for the first time the hard evidence that primary cosmic rays were not that idealized, uniform, primitive 'cosmic' gas, matter made up solely of the most primitive of atoms in headlong motion. They were in fact a complicated sampling of the ordinary matter of sun and stars, right here in the disc of the Milky Way.

Starstuff is itself rather uniform. It is mainly hydrogen like the cosmic rays. But it is not at all chemically pure, mysteriously simple, reagent hydrogen; rather it is hydrogen of technical grade, clearly mixed with five or ten per cent by weight of a dominant helium impurity, plus a little more of many, many heavier nuclear species: starstuff. The cosmic-ray chemical samples first put into evidence were brought back from stratospheric balloons floating high above 98 or 99 per cent of our shielding atmosphere. The big balloons carried a sensitive detecting payload, thin films of photographic emulsion. Once recovered, developed, and painstakingly scanned under the microscope, long coherent wakes of developed silver grains in the emulsion layer unmistakably recorded the passage of fast multiply charged ions of many familiar elements. Recognition of unity was quick and it was firm. By now those results are very much elaborated, in as much quantitative detail as the label on a bottle of first-rate laboratory reagent.

The 1948 paper, brilliantly conceived and technically expert, was the first post-war work of physicist Bernard Peters. For me it opened a new world, into which I moved slowly step by step from theoretical nuclear physics to the astronomy of high energies that enfolds me to this day. Peters and Bradt had given every investigator who came after them the full courage to study cosmic rays as another part of the vast astronomical world, curious wanderers to be sure, but only an unusual constituent of the inclusive, familiar whole.

Heaven and earth are of one stuff indeed.

By 1950 the first few experimenters sampling the nearest edge of space could use the sample to set limits on the history of the wandering particles. They could estimate from the composition of the incomers the time of storage and the distance made good since those particles were first accelerated to cosmic-ray energy. For the rays must traverse interstellar space, which is not utterly empty, and there from time to time they collide with the dilute thermal gas in space, itself mainly hydrogen.

The secondary products of any such collisions far out in space become a part of the incoming 'primaries' here on earth. The number and nature of the products — other nuclear isotopes and electrons and even positrons—show that the wandering protons must have been stored in space for a time orders of magnitude longer than the mean time for the arrival of light from the stars, which is something like the averaged transit time for light across the galaxy, some tens of thousands of light years. That makes sense, for it reconciles the fact that the energy density of starlight and of cosmic rays are about the same, although cosmic rays surely have unusual source, while starlight pours from every star. So began the dating of cosmic rays and the long and difficult search for their regions of origin.

Cosmic rays are stored up in space; they do not march out of the galaxy into all of space at full speed, as starlight does. The reason is evident. Charged particles cannot move in space along straight lines, but diffuse waywardly from the sources through the intricate magnetic fields of our magnetic galaxy, as photons diffuse through fog. Dust-free space is transparent to light, but a dense fog to particles that feel magnetic forces. We cannot expect to see any cosmic-ray stars show up as point-peaks of intensity; cosmic-ray astronomers have to try to build up their source maps without appeal to direct lines of sight. (Only the sun is so close to us that we recognize it as an occasional transient source of a small portion of the cosmic rays.)

Small variations of intensity and direction can and do show diffusion gradients in the galactic cosmic-ray gas, but for the most part we cannot trace back a proton to any particular distant source as we can follow a ray of light or of any other uncharged component to its real origin.

These ideas, all still under quantitative study, flowed from the post-war results that first showed the primary rays to be worldstuff like ourselves. I leave to others — perhaps to Bernard himself — to talk about the exciting part taken by the Indian physicists in the worldwide unravelling of the rays and in the search for their origins, after fifty years by no means a settled matter, one probably more complicated than we like to admit.

Most clues point to magnetic interactions as the cause of acceleration of the charged rays, energy added steadily by moving macroscopic magnetic fields, not impulsively by some unknown events. In the frame of the particles a magnetic field carried by any moving plasma is seen as an electric field, and is thus an energy-giver. The individual particle is in a way trying to come into energy equipartition with an enormously larger moving mass, whose mass and kinetic energy are incomparably larger than that of any single cosmic ray, a mass that carries magnetic lines of force on macroscopic spatial scale. The 'high energy' of a single cosmic-ray proton is tiny on such a scale; the process of equipartition is limited so that the proton takes up plenty of energy for one lone particle, as much as a few joules for the highest-energy cosmic rays, so that we call the rays high-energy. It is the energy per particle that we describe as high; a joule is not much energy for any astronomical structure. The total power of the cosmic rays that enter earth is no more than the power in ordinary starlight. It is the energy concentration that astonishes.

There are many possibilities for energy exchange between the macroscopic world and some lone proton. Perhaps the magnetic field that pushes the proton, whether only once, or time and time again, is generated by the electric currents that fill a vast slow-moving cloud of magnetized plasma, some large feature of the orbiting galactic gas. Perhaps it is found in a smaller, but still enormous, moving shock front light years across, generated by some stellar explosion, likely a supernova. Perhaps it is smaller, star-sized shocks from a magnetic flare on the surface of some star, like those we see close by on the sun. Perhaps it is an entire spinning, magnetized neutron star the size of a mountain that can share rotational kinetic energy as its rotating pattern of magnetic field sweeps past the proton. We have evidence for distant spinning quasar discs as big as the solar system. Those might be the energy-rich magnetized sources of the relativistic electron pools that we know to power the giant radio sources far away from our galaxy; possibly the cosmic-ray protons are out there as well. (We cannot detect the protons by their radio emission, for particles so massive accelerate slowly and radiate too little. Big enough pools of cosmic-ray protons can be mapped at a distance for example in the disc of our own galaxy, by detection of the gamma rays they make as the products of occasional collision against the dilute gases of space. The gamma rays bring us signs of far-off cosmic rays along the straight-line path that is denied to the protons themselves.

All of these places, and more too, are among the sources of the cosmic rays we study; we are not yet able to assess fully their several roles in the whole story. But for all that variety of astronomical source environment the primary rays themselves are more or less ordinary, familiar ions in the natural world, mostly, but by no means all of them, protons. They gain their astonishing energy not in some unique mystery of creation, but by pushes they underwent wherever they happened to be in the evolving context. Some are the products of secondary collision. The cosmic rays are part and parcel of the material whole, as much as the stars themselves.

The foundation for that unifying insight was well laid by young Peters and his young friends back in 1948.

The perils of the sceptic

We were pretty surely right to seek the unity of the material world, and to deny that cosmic rays must be broken away from the rest of astrophysics. But that insistence can also be wrong, however satisfying to our hopes; the physicist should not be beholden to any special metaphysics, even to simplicity. Nature decides. Newton himself violated the fine physical intuition and high sense of unity of his great colleagues by his blithe willingness to use the daring notion of action at a distance, his simple unexplained law of the inverse square for gravitation. He would make no hypotheses, he said, about the state of the medium between the attracting masses. The great Huyghens was openly a little scandalized, and even said aloud that he hoped for a real mechanical theory from Newton, not merely talk of occult forces. But Newton enabled so much progress with a simple formula, and his universal force was so plainly demonstrated here on earth, that his law still leads us. That incomplete but amazingly precise description far outlasts the vague, impractical vortices his less incisive contemporaries sought out, however metaphysically correct they may have been, viewed in the light of the geometrical theory that came much later.

As much as we enjoy the unity of matter that has, since 1948, placed the once-ineffable cosmic rays squarely within the real, impure astronomical world, we have ourselves come to a new time of metaphysical strangeness that seems all the same to have ample support from theory and experiment. It remains short of final demonstration, yet the amazing simplicity of the cosmic microwave background has placed us once again into a stance where the simplest material unity we hoped for the world may have to be denied.

The relativistic early cosmological stage that is dubbed inflation gives a clear dynamical account of the best-measured results in all of cosmology, the thermal background. The featureless hot radiating plasma that we record at far distances, well behind all the irregular, clumpy matter we see, is fully interpreted by inflation (itself outside the scope of these lines). We have long recognized that some dark unseen matter of some sort, perhaps only dark, cold, little failed stars, was copious in the galaxies and their halos. Now the inflation theory all but demands a cosmos that has one or two orders of magnitude more dark matter than all that we can see radiating through any of the electromagnetic channels we now master, much more of it even than the best estimates of how much ordinary baryonic matter can be present, much heavier than all the stars, the gas, and the dust.

The good predictions of the pre-stellar, primordial production of helium and deuterium is what limits baryonic matter strongly. That prediction too stands on a strong base. Very old 'metal-poor' stars and gaseous clouds are directly seen to contain 25% of helium by weight, close to the amount we impute to the sun. But those same samples may have only a fiftieth part of the sun's small content of the heavier elements! That minimal, ubiquitous helium was formed before any of the galaxies or stars; the oldest stars are rich in it. The cosmologists can say just when and how the helium was made in a smooth, bland cosmic volume filled with a very hot gas of neutrons and protons, electrons and photons. (A few light isotopes are made there as well in trace amounts that fit the best measurements.) Hydrogen and helium are of cosmological origins; the stars made all the rest—which is not much.

We have come to an odd metaphysical stance. Old Copernicus could see the planets easily; he showed that our green earth, so close to us that it looked much different, was just one more shining planet among the planets, nothing so special. So for gravitating matter, and so also for the atoms. They are universal. So also for the cosmic rays. They are just matter like ourselves, only much energized, just as shining, artificial satellites are highly energized machine-shop artefacts, made by human hands, of samples of a single familiar mix of atoms.

Now we are told that most of the mass of the cosmos is a new kind of matter whose very name we do not know; it gravitates, but does not interact detectably either with electromagnetic fields or with the forces that bind the nucleons. For the first time we find that it is not the matter of everyday experience that fills the cosmos; the situation is anti-Copernican for the first time since Anaxagoras. Space does not appear to be filled with dark, cold stones or with anything like them, but with axions or photinos or some other still conjectural particles, predicted by field theory from new and tempting symmetries that so far have found no experimental support.

The most palatable proposal for such novelties, made very early by Ramanath Cowsik at the Tata Institute of Fundamental Research (see ref. 2), fills our world with unseen massive neutrinos of one or another flavour, though so far that proposal does not seem to work in

Felix: an extended acknowledgement

Readers may on this special occasion pardon a rather personal digression. I write a little not of physics, but of physicists.

We were a dozen young graduate students of theoretical physics in the group around Robert Oppenheimer at Berkeley during the late thirties. I can easily recall my first encounter with a new student, Bernard Peters, now more than fifty years ago. He seemed a little different from us, more mature, marked with a special seriousness and intensity. He was a little older than most of us, but his experience went far beyond ours. He was a European, who had seen and felt the barbarous darkness that mantled Nazi Germany; then he had worked for a living among the longshoremen in San Francisco Bay. In contrast, we were only North American students, largely innocent save by hearsay and our eager reading, of most of life beyond the campus and overseas.

Bernard's wit and playful spirit, personal affection and deep generosity were in no way muffled by his patent maturity. The time came when I had to leave Berkeley to take up a first teaching post across the Bay in San Francisco. I was a poor enough graduate student; we had no car, though plainly it would become very welcome, once my wife and I lived so far from the Berkeley campus that visits would be long journeys.

Sure enough, Bernard had an answer—generous, delightful, and effective. He would give us an automobile! It had long served Bernard and Hannah, and they could manage a change. They had named their loyal old vehicle Felix. Felix, a hardworking veteran Ford, became ours. Up and down the roads he carried us in pleasure, happy as the Latin meaning of his name.

Felix had one failing, a bad drinking habit. Let me expand on the analogy: all cars live on a liquid diet. But it is clear that their nutritive food is their fuel, gasoline (petrol). The lubricating oil they must also sparingly use is something extra, not unlike the alcoholic beverages many humans take moderately, not for nutrition but for other internal reasons. Poor Felix was a lubriholic. Where most automobiles take a few quarts of engine oil each month or two of work, Felix consumed the thick delicious stuff at easily ten times that rate, a quart of oil to enrich every few gallons of gas (1 US gallon = 4 US quarts = 3.785 litres).

Whenever my wife Emily, who was then the driver in our family, guided hungry Felix into a petrol station, my work was routine. Once the attendant had fed Felix, and gotten his pay, I would lift off the back-seat floor a big square multigallon can we always kept at hand. It was the economy-sized package of the cheapest lubricating oil we could buy. I would open the hood, lift Felix's filler cap, and satisfy poor Felix's habit from the big can, until the next time we had to stop for gas. Only so could we support thirsty Felix as he puffed his way along the roads of northern California, a thin blue stream of tailpipe smoke always behind.

Our student days are long gone. The Berkeley friends were dispersed by the usual academic pilgrimages, then scattered by the exigent years of World War II, and parted indeed by decades of Cold War that led Bernard to a physicist's life in Bombay. I am happy to evoke our fifty years of friendship inside the diffuse little republic of physics, and to wish for him the high hopes we share: a better physics to come than we old-timers have yet seen, and a century of change far beyond the laboratories towards a world wherein reason will be more at home, and justice widespread.

detail. Neutrinos, while not exactly everyday matter, are at least no strangers in the laboratory or to astronomers. If they were the dark matter, we could see a unity in matter as we see in the chemistry of our earth: silicon and oxygen and iron are plentiful here in the rocks, though in sun and stars those atoms are found only in parts per thousand. Still, they are present, to imply a deep unity within. That unity is simply locally disturbed, but not destroyed, by those complex physicochemical processes that formed our unusual, extra-dense home planet, collecting up oxygen, even iron, but losing light, fugitive hydrogen.

Experience must one day decide. Something of the spirit of old Copernicus will hold: our earthly home seemed special, but was not. So too our kind of matter, made of nucleons and electrons, seemed prevalent, but perhaps it is not. The real unity we seek is not of the familiar alone; that seems too narrow for an unbiased view. It is rather a unity of the demonstrable, a unity that joins all the processes we can grasp. The next decade or so may begin to bring an answer.

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1. Freier, P., Lofgren, E. J., Ney, E. P. and Oppenheimer, F., *Phys. Rev.*, 1948, **74**, 1818; Bradt, H. L. and Peters, B., *Phys. Rev.*, 1948, **74**, 1828, and 1950, **80**, 943.

The two citations appeared in 1948 as adjoining papers. The FLNO group at the University of Minnesota flew a cloud chamber, and saw heavy primary tracks; the BP group at the University of Rochester flew emulsions that also showed heavy tracks. The simultaneous confirmation was not accidental. F. Oppenheimer and B. Peters had been close friends and colleagues at Berkeley; the two parallel experiments were carried on in quite friendly rivalry. The emulsion technique turned out to be more open to later development.

2. Reviewed nicely in *Cosmic Pathways*, (ed. Cowsik, Ramanath), Tata McGraw-Hill, New Delhi, 1986, pp. 289–310.

The present scope of the field of terrestrial cosmogenic nuclides

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The discovery of natural radiocarbon produced by cosmic rays in the earth's atmosphere by Libby in the late forties[1–3] was followed by the discovery[4] of terrestrial cosmogenic nuclide ^{3}H in 1951. In the next few years several terrestrial cosmogenic radionuclides were detected[5]. The cosmogenic nuclides found a variety of new applications during 1960–1970 in meteorology, hydrology, glaciology and oceanography. The three long-lived cosmogenic nuclides produced in the atmosphere with half-lives > 100 yr, ^{32}Si, ^{14}C, ^{26}Al and ^{10}Be continued to provide invaluable data in the field of oceanography, using the methods developed in the sixties. However, in the late seventies the development of the accelerator mass spectrometry (AMS) technique made it possible to measure several long-lived radionuclides[6,7] with 3–6 orders of magnitude higher sensitivity. This led to an explosion in the eighties in the scope of applications of cosmogenic nuclides in both terrestrial and extraterrestrial samples. This article attempts to convey the sense of the present excitement of cosmogenic nuclides as tools in geosciences, while highlighting the modern development with perspectives of the forties and fifties when the terrestrial cosmogenic nuclides ^{14}C, ^{3}H, ^{10}Be and others were discovered.

'Cosmic-ray physics, which ten years ago was a fairly specialized branch of science, has in the course of its recent development become closely linked with many other fields of research; it has become an integral part of astrophysics, radioastronomy, and solar physics; it has made important contributions to such diverse fields as geomagnetism, hydrology, and archaeology, and has begun to gain some importance in the study of meteorites and of oceanography and meteorology. It has also given rise to one of the newest and most active branches of physics, particle physics,....' Bernard Peters[8] said this in a paper 'Progress in cosmic-ray research since 1947' published in 1959. During that interval, Peters was himself responsible for several of the developments mentioned: in cosmic-ray physics (origin, propagation and lifetime of cosmic rays; nature of nuclear interactions of high-energy cosmic-ray particles, discovery of multiply charged nuclei in cosmic radiation, characterization of several elementary particles), and in the field of cosmic ray-produced isotopes on the earth. Peters had already carried out a tremendous amount of original work on the nature of primary cosmic radiation during his stay at the