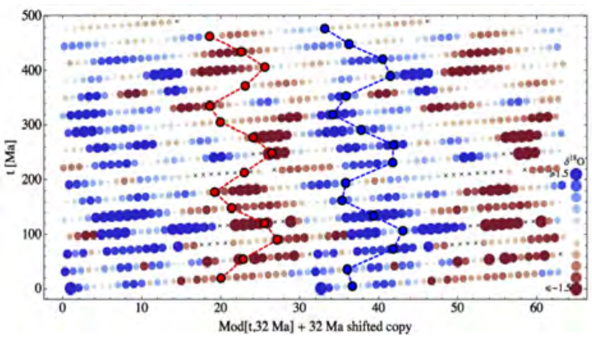
Institute for Advanced Study   Fall/Winter 2014–15

Sights from a Field Trip in the Milky Way: From Paleoclimatology to Dark Matter

How is climate influenced by cosmic rays?



Our galactic journey imprinted in the climate—when Earth's temperature (red dots warm, blue dots cold) is plotted as a function of time (vertical axis) and as a function of time folded over a 32-million-year period (horizontal axis), the 32-million-year oscillation of the solar system relative to the galactic plane is evident.

BY NIR SHAVIV

In 1913, Victor Hess measured the background level of atmospheric ionization while ascending with a balloon. By doing so, he discovered that Earth is continuously bathed in ionizing radiation. These cosmic rays primarily consist of protons and heavier nuclei with energies between their rest mass and a trillion times larger. In 1934, Walter Baade and Fritz Zwicky suggested that cosmic rays originate from supernovae, the explosive death of massive stars. However, only in 2013 was it directly proved, using gamma-ray observations with the FERMI satellite, that cosmic rays are indeed accelerated by supernova remnants. Thus, the amount of ionization in the lower atmosphere is almost entirely governed by supernova explosions that took place in the solar system's galactic neighborhood in the past twenty million years or so.

Besides being messengers from ancient explosions, cosmic rays are extremely

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An Historical Approach to Islamic Theology

Tracing modern Islamic thought back to the Middle Ages

Hassan Ansari (right) with Professor Sabine Schmidtke

When Sabine Schmidtke and Hassan Ansari, an Iranian national, met more than a decade ago in Tehran, Ansari was a student of the traditional religious system in Qum and Tehran (the "Hawza"). Ansari had read Schmidtke's doctoral thesis *The Theology of al-ʿAllāma al-Ḥillī (d. 726/1325)*, which was translated into Persian and published in Iran in 1999. Schmidtke's scholarship changed Ansari's approach to Islamic sources and was one of the reasons why he became interested in historical studies on Islamic theology. "The historical approach is not only useful, it is necessary," says Ansari. "I talk now as a Muslim scholar. We need to have this kind of historical studies to change our approach to our own intellectual and legal tradition and its holy texts."

What makes Ansari a particularly exceptional scholar is his combination of Western and traditionalist Islamic training. In the "Hawza" in Qum and Tehran, he successfully completed the very highest level of study for the rank of Ayatollah, in the Shiʿi clerical system. He also has studied Islamic and Western philosophy and Islamic intellectual history at universities in Tehran, Beirut, and Paris. "Hassan's command of the sources is extremely wide-ranging," says Schmidtke, "and he combines this

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Through the Lens of Computation

Computational theory's deepening role in physics, social sciences, economics, and biology

How do computer scientists view natural and social phenomena? How can patterns of information be described algorithmically and studied through computational models and techniques? And what new computational models does nature itself suggest?

In November, Avi Wigderson, Herbert H. Maass Professor in the School of Mathematics, organized the conference "Lens of Computation on the Sciences," which explored the increasing interactions of computational theory with physics, social sciences, economics, and biology.

The theory of computation—the study of the mathematical foundations of computer science and technology—dates back to 1936, with Alan Turing's thesis "On Computable Numbers, with an Application to the Entscheidungsproblem," which introduced a mathematical model of a computer known as the Turing machine. Also known as the Church-Turing thesis, it states that not every problem is solvable by a computer but all efficient computations can be simulated by such a machine. For nearly eight decades, computational theory has been used to develop models for various computational devices, study the power and limits of these devices to solve computational problems, develop algorithms and understand the computational intractability of certain problems, and

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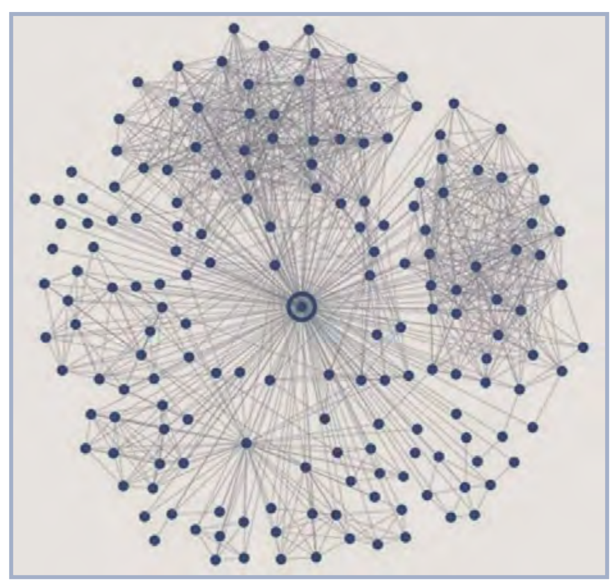
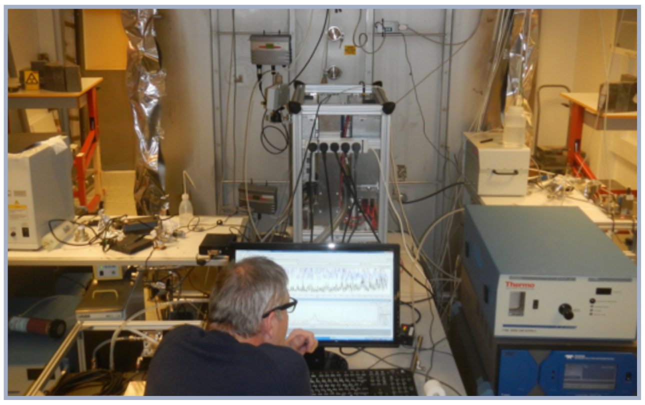


Given a person's Facebook network (at right), can we identify their most significant social ties? Sociologist Jon Kleinberg and colleagues have moved beyond the idea of embeddedness—which measures the number of mutual friends and the strength of such connections—to ask: Given a Facebook user who is in a relationship, can their relationship partner be found from the pure network structure? Are there structural signatures for other kinds of roles? How does this relate to the way information flows through these networks?

interesting because they link together so many different phenomena. They tell us about the galactic geography, about the history of meteorites or of solar activity, they can potentially tell us about the existence of dark matter, and apparently they can even affect climate here on Earth. They can explain many of the past climate variations, which in turn can be used to study the Milky Way.

The idea that cosmic rays may affect climate through modulation of the cosmic ray ionization in the atmosphere goes back to Edward Ney in 1959. It was known that solar wind modulates the flux of cosmic rays reaching Earth—a high solar activity deflects more of the cosmic rays reaching the inner solar system, and with it reduces the atmospheric ionization. Ney raised the idea that this ionization could have some climatic effect. This would immediately link solar activity with climate variations, and explain things like the little ice age during the Maunder minimum, when sunspots were a rare occurrence on the solar surface.

In the 1990s, Henrik Svensmark from Copenhagen brought the first empirical evidence of this link in the form of a correlation between cloud cover and the cosmic ray flux variations over the solar cycle. This link was later supported with further evidence including climate correlations with cosmic ray flux variations that are independent of solar activity, as I describe below, and, more recently, with laboratory experiments showing how ions play a role in the nucleation of small aerosols and their growth to larger ones.



Henrik Svensmark is using the gamma-ray irradiated chamber in the background to understand the effect of cosmic rays on climate by pinpointing the mechanism linking atmospheric ions and cloud condensation nuclei.

In 2000, I was asked by a German colleague about possible effects that supernovae could have on life on Earth. After researching a bit, I stumbled on Svensmark's results and realized that the solar system's galactic environment should be changing on time scales of tens of millions of years. If cosmic rays affect the terrestrial climate, we should see a clear signature of the galactic spiral arm passages in the paleoclimatic data, through which we pass every 150 million years. This is because spiral arms are the regions where most supernovae take place in our galaxy. Little did I know, it would take me on a still ongoing field trip to the Milky Way.

The main evidence linking the galactic environment and climate on Earth is the exposure ages of iron meteorites. Exposure ages of meteorites are the inferred duration between their breakup from their parent bodies and their penetration into Earth's atmosphere. They are obtained by measuring the radioactive and stable isotopes accumulated through interaction with the cosmic rays perfusing the solar system. It turns out that if one looks at exposure ages a bit differently than previously done, by assuming that meteorites form at a statistically constant rate while the cosmic ray flux can vary, as opposed to the opposite, then the cosmic ray flux history can be reconstructed. It exhibits seven clear cycles, which coincide with the seven periods of ice-age epochs that took place over the past billion years. On longer time scales, it is possible to reconstruct the overall cosmic ray flux variations from a changed star formation rate in the Milky Way, though less reliably. The variable star formation rate can explain why ice-age epochs existed over the past billion years and between one and two billion years ago, but not in other eons.

I later joined forces with Canadian geochemist Ján Veizer who had the best geochemical reconstruction of the temperature over the past half billion years, during which multicellular life left fossils for his group to dig and measure. His original goal was to fingerprint the role of CO_2 over geological time scales, but no correlation with the paleotemperature was apparent. On the other hand, his temperature reconstruction fit the cosmic ray reconstruction like a glove. When we published these results, we instantly became personae non gratae in certain communities, not because we offered a data-supported explanation to the long-term climate variations, but because we dared say that CO_2 can at most have a modest effect on the global temperature.

Besides the spiral arm passages, our galactic motion should give rise to a faster cosmic ray flux modulation—in addition to the solar system's orbit around the galaxy, with roughly a 250-million-year period, the solar system also oscillates perpendicular to the galactic plane. Since the cosmic ray density is higher at the plane, it should be colder every time the solar system crosses it, which depending on the exact amount of mass in the disk should be every 30 to 40 million years.

A decade ago, the geochemical climate record showed hints of a 32-million-year periodicity, with peak cooling taking place a few million years ago, as expected from the last plane passage. Together with Veizer and a third colleague, Andreas Prokoph, we then submitted a first version for publication. However, we actually ended up putting the paper aside for almost a decade because of two nagging inconsistencies.

First, analysis of the best database of the kinematics of nearby stars, that of the Hipparcos satellite, pointed to a low density at the galactic plane, which in turn implied a longer period for the plane crossings, around once every 40 million years. Second, it was widely accepted in the cosmic ray community that cosmic rays should be diffusing around the galactic disk in a halo that is much larger than the stellar disk itself. This would imply that the 300 light years that the solar system ventures away from the galactic plane could not explain the 1 to 2°C variations implied for the geochemical record. Without a way to reconcile these, there was not much we could do. Perhaps the 32 million years was just a random artifact.

As time progressed, however, the improved geochemical record only showed that the 32-million-year signal became more prominent. In fact, fifteen cycles could now be clearly seen in the data. But something else also happened. My colleagues and I began to systematically study cosmic ray diffusion in the Milky Way while alleviating the standard assumption that everyone had until then assumed—that the sources are distributed symmetrically around the galaxy. To our surprise, it did much more than just explain the meteoritic measurements of a variable cosmic ray flux. It provided an explanation to the so-called Pamela anomaly, a cosmic ray positron excess that was argued by many to be the telltale signature of dark matter decay. It also explained the behavior of secondary cosmic rays produced along the way. But in order for the results to be consistent with the range of observations, the cosmic ray diffusion model had to include a smaller halo, one that more closely resembles the disk. In such a halo, the vertical oscillation of the solar system should have left an imprint in the geochemical record not unlike the one detected.

Thus, armed with the smaller halo and a more prominent paleoclimate signal, we decided to clear the dust off the old paper. The first surprise came when studying the up-to-date data. It revealed that the 32-million-year signal also has a secondary frequency modulation, that is, it is periodically either slower or longer. This modulation has a period and phase corresponding to the radial oscillations that the solar system exhibits while revolving around the galaxy. When it is closer to the galactic center, the higher density at the galactic plane forces it to oscillate faster, while when far from the center, the density is lower and the oscillation period is longer.

The second surprise came when studying the stellar kinematics from the astrometric data. We found that the previous analysis, which appeared to have been inconsistent, relied on the assumption that the stars are more kinematically relaxed then they are. As a consequence, there was a large unaccounted systematic error—without it there was no real inconsistency. It took almost a decade, but things finally fell into place.

The results have two particularly interesting implications. First, they bring yet another link between the galactic environment and the terrestrial climate. Although there is no direct evidence that cosmic rays are the actual link on the 32-million-year time scale, as far as we know, they are the only link that can explain these observations. This in turn strengthens the idea that cosmic ray variations through solar activity affect the climate. In this picture, solar activity increase is responsible for about half of the twentieth-century global warming through a reduction of the cosmic ray flux, leaving less to be explained by anthropogenic activity. Also, in this picture, climate sensitivity is on the low side (perhaps 1 to 1.5°C increase per CO_2 doubling, compared with the 1.5 to 4.5°C range advocated by the IPCC), implying that the future is not as dire as often prophesied.

The second interesting implication is the actual value of the 32-million-year oscillation. The relatively short period indicates that there is more mass in the galactic plane than accounted for in stars and interstellar gas, leaving the remainder as dark matter. However, this amount of dark matter is more than would be expected if it were distributed sparsely in a puffed-up halo as is generally expected. In other words, this excess mass requires at least some of the dark matter to condense into the disk. If correct, it will close a circle that started in the 1960s when Edward Hill and Jan Oort suggested, based on kinematic evidence, that there is more matter at the plane than observed. This inconsistency and indirect evidence for dark matter was also advocated by John Bahcall, who for many years was a Faculty member here at the IAS.

It should be noted that the idea that cosmic rays affect the climate is by no means generally accepted. The link is contentious and it has attracted significant opponents over the years because of its ramifications to our understanding of recent and future climate change. For it to be finally accepted, one has to understand all the microphysics and chemistry associated with it. For this reason, we are now carrying out a lab experiment to pinpoint the mechanism responsible for linking atmospheric ions and cloud condensation nuclei. This should solidify a complete theory to explain the empirical evidence.

As for the existence of more dark matter in the galactic plane than naively expected, we will not have to wait long for it to be corroborated (or refuted). The GAIA astrometric satellite mapping the kinematics of stars to unprecedented accuracy will allow for a much better measurement of the density at the plane. The first release of data is expected to be in 2016, just around the corner. ■

Nir Shaviv, IBM Einstein Fellow and Member in the School of Natural Sciences, is focusing on cosmic ray diffusion in the dynamic galaxy, the solar cosmic ray–climate link, and the appearance of extremely luminous (super-Eddington) states in stellar evolution during his stay at the Institute. Shaviv is Professor at the Racah Institute of Physics at the Hebrew University of Jerusalem.