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Some Personal Conclusions

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Abstract

I present here some personal considerations on the main theoretical, observational and technological challenges offered to the discussion during the Meeting "Multifrequency Behaviour of High Energy Cosmic Sources".

1 The Theme

This Meeting presented a wide collection of excellent results on a wide range of subjects in modern multi-frequency astrophysics. I am not able to remember a single talk that did not produce a vibrant discussion in and out of the audience.

Beyond any attempt to summarize the outcomes of the Meeting, it seems more appropriate for me to briefly present here some personal considerations on the main challenges offered to the discussion during this Meeting.

2 The Challenges

One of the main aspects of this Meeting is its capacity to induce global discussions on some of the most important challenges in astrophysics and cosmology. These challenges address the nature of fundamental questions in the physics of the universe, the frontier of exa-scale data mining and analysis and the technological challenges related to the construction of the largest astronomical facilities in the next decade.

2.1 Theoretical challenges: fundamental questions

Big theoretical challenges regard two important aspects of the structure and evolution of our universe: the cosmic origins and the cosmic extremes.

Origins. Beyond the successes of the standard cosmological scenario, we are still facing some crucial questions:

What Happened at the Beginning of the Universe? Inflation and Precision Cosmology. There's been incredible progress recently in finding the traces that inflation left behind and upcoming experiments on CMB polarization promise to provide even more evidence of what happened during the universe's infancy. Through its sensitivity to gravitational waves, the study of the CMB provides a glimpse into the state of the universe just $\sim 10^{-35}$ seconds after the beginning and of physics on grand-unification-theory (GUT) energy scales around $\sim 10^{16}$ GeV, some ≈ 13 orders of magnitude above the energies achievable by current terrestrial particle accelerators. A gravitational-wave background in the early universe would leave a unique, odd-parity pattern of polarization in the CMB (B-modes), the magnitude of which is characterized by the tensor-to-scalar ratio r. A GWB is generically predicted to exist by inflationary theories, and the current generation of CMB polarization experiments will probe the interesting parameter space of $r \lesssim 0.05$ corresponding to single-field inflationary models at GUT scales. The challenges here seem to be a statistically confident measurements of B-modes and the imperative study of the systematics that are present in such a difficult measurement. A multi-frequency study of B-modes with extremely high sensitivity, over a wide range of frequencies and large sky areas would likely be able to measure in the not-so-distant future the value of r with a $\sim 10\%$ precision and will open the field to a deep theoretical exploration of inflationary cosmologies.

What is the Dark Matter? This is a particularly exciting time for dark matter study because there are some intriguing clues pointing to where dark matter particles might be hiding. These clues are helping researchers develop a variety of searches. The three major strategies are direct detection, collider production and indirect detection. While there is a mounting scientific frustration in the non conclusive evidence for the detection of DM particles with direct and collider detection techniques, the sensitivity and the specific strategy of the next coming astronomical observatories (mainly the CTA and the SKA) will probably allow in the next decade to shed a conclusive word on the nature of DM, or close a large fraction of the DM parameter space and thus open the way to a more detailed exploration of realistic alternatives of the theory of Gravity.

What Makes Up the Rest of the Universe? Dark Energy. In the past 15 years or so, scientists have realized that the "stuff" making up all the atoms in all the galaxies, stars, planets, and humans we have ever observed only constitutes about 5% of the universe. While we might be close to pinning down the nature of part ($\approx$ 27%) of the missing stuff (e.g., dark matter), what we know about the dominant ($\approx$ 68%) component of the universe, (named historically dark energy for a vague analogy with DM) is still almost nothing. Observational efforts are planned (e.g., EUCLID, SKA, DES, LSST, etc.) and theoretical exercises to narrow down the available DE parameter space are the subject of a restless activity, but a detailed physical characterization of the "dark energy" is still missing and probably this theoretical activity will be very relevant in pointing at the true nature of the physical mechanism providing the late-stage cosmic acceleration.

Extremes.

Where Did That Come From? Cosmic Rays and Intergalactic Particle Accelerators. After a century of study, researchers still struggle to understand the origin of cosmic rays, and especially those of ultra high energy. We believe these extreme high-energy oddities play a key role influencing the physics and chemistry that form stars and planets, and even influence life on Earth by occasionally causing mutations in DNA. And yet, the exact ways in which cosmic rays are accelerated remains a major open question. We've discovered where many come from within our galaxy, but the most extreme cosmic rays continue to confound us. The need of a very large collecting area experiment for the extremely rare UHECR events poses several observational challenges, but its delivery will probably open the way to a physical clarification of their origin and of the production sites. Challenges to particle acceleration theories in cosmic structures are stronger and stronger and the scientific qualification of the possible product sites is reducing more and more towards regions of compact objects with extremely strong gravitational fields and magnetic fields.

What Can Compact Objects Teach Us? Black Holes and Neutron Stars, Extreme Physics in Small Packages. Enormously powerful gravitational fields that warp the local fabric of space and time. Incomparably strong magnetic fields that can stretch atoms themselves into long spindles. Materials so dense a teaspoonful would weigh billions of tons. These are just some of the exotic properties of compact objects, a catch-all term for several types of unbelievably dense and remarkable objects, like white dwarfs, neutron stars and black holes. Compact objects are known to possess some of the most extreme physical properties ever observed. Scattered throughout our galaxy and AGNs, these objects serve as astrophysical laboratories that test the very limits of physics as we know it.

2.2 Observational: big data science

It is now becoming clear that the answers to big questions in astrophysics and cosmology requires to address the challenge of dealing with big data quantities, analysis and transport.

How Will We Make Sense of It All? Astronomically Big Data. Astrophysics and cosmology deal with big everything: big datasets, big simulations and big collaborations. We have information on billions of astronomical objects, and expect to make measurements of many billions more in the next decade. Yet the challenge with such a large dataset is not so much in handling its size, but in its complexity. The struggle in trying to find a single rare star in a haystack of billions of near-identical stars, or understanding the relationships between every single galaxy in the universe, goes beyond simply the enormous number of gigabytes. As more and more data piles up, the teams who are most innovative about analyzing and combining those datasets will be the ones who will likely make the biggest discoveries. Instruments like the SKA will fully live into the era of big data complexity and will have to address not just the complex techniques of data reduction and analysis, but also the challenges of data distribution and transport over inter-continental distances and yet with high computing capacity on our everyday desktop computer. The next generation of astronomical surveys (and even single observations) will contain information that spans multiple frequencies, and many epochs in time. However there is not yet a next generation of catalog than can describe these surveys. A more meaningful description of catalog data will ultimately lead to better comparisons of astronomical surveys and more robust scientific output. It is not unreasonable that a stratification of various computational tasks and a possible re-definition of the data analysis objectives and techniques will be (re-)considered in the light of the experimental and theoretical challenges of the next decade big astronomy science. In this context, small or mid-size multifrequency data centers will probably play a major role in developing innovative applications for (astronomical) data science and producing cutting edge scientific exploitation of the data achieved by large astronomical facilities.

2.3 Experimental: big facilities

The future large astronomical projects will live inherently in the era of multifrequency astronomy. Examples of this synergy are provided by the SKA, the CTA, the LSST, and the largest future space missions like e.g.

EUCLID, Millimetron. The wealth of planed astronomy projects is such that it seems that the future of astronomy can only be limited by the financial constraints of international funding available. Both ground-based and space-borne experiments are facing challenges specific to their different nature. Some of these are technical and will give rise to extensive technological developments and innovations. Some other are programmatic and are related to the complex and ambitious nature of future projects. It is not unlikely that the complementarity between large-scale projects and pathfinders will provide the scientific community the clarity on the technological routes to be followed for the construction of the most successful and challenging astronomical facilities of the next decade, as well as the directions in the optimal integration of these facilities in the most successful multifrequency strategy. This seems to be mandatory in order to answer the remaining big questions on the nature and the evolution of our universe.

3 Predictions

Based on the decennial successes of this Meeting, as also testified by this specific one, it is not difficult to predict that the next Meeting of this series will provide an even more extended discussion on the major challenges of multifrequency astrophysics, cosmology and astro-particle physics in the next future.

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