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FOLLOWING THE EVOLUTION OF STARS, GLOBULAR CLUSTERS AND SPIRAL GALAXIES

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The following interview has been translated into the Czech language and extended in the reference [2].

Jana Žďárská: You deal with many scientific questions, for example, dynamical properties of stellar systems (IMF, multiplicity), evolution of young multiple stellar systems in birth aggregates, star formation, dynamical evolution of open and globular clusters, spatial and kinematical distribution of stars, origin of field stars, structure and mass of the Galaxy, galactic dynamics, formation and evolution of dwarf satellite galaxies, dark matter content of galaxies. Could you kindly tell us which of these scientific topics is the most interesting for you?

Pavel Kroupa: The greatest question I am perhaps mostly interested in now is to understand how galaxies evolve. Given al the observations and calculations performed to date, dark matter does not exist. This can be written with the greatest of certainty. The vast number of galaxies are, like our Milky Way, star-forming disk galaxies. These need to constantly be supplied by gas, as otherwise they would stop forming stars. Where does this gas come from? And, why are all galaxies of a similar mass so incredibly similar to each other? These questions are touching on our deepest level of understanding of space-time-matter physics, and I have been developing some rather exciting ideas on how to possibly advance our understanding.

J.Ž.: Two years ago you participated at the conference Cosmology on Small Scales 2016: Local Hubble Expansion and Selected Controversies in Cosmology held in Prague. What is your opinion on this issue?

P.K.: I do not have an opinion concerning any of the questions, but the observational data show that there is something very wrong in our current understanding. The counts of galaxies with distance tell us that we are situated in a huge under density which has a radius of about 1 200 million light years. This is completely in contradiction with any cosmological model, and is also largely ignored by the community. But such a huge under density must have a big effect on local expansion and also implies that our understanding of cosmology is currently not correct.

J.Ž: There exist about 150 globular clusters in the Milky Way. They are very old systems and contain hundreds of thousands or up to millions of stars. Do you know how globular clusters looked like ten billion years ago?

P.K.: Most of the globular clusters would have been already about 2 billion years old. They would have been 10 to 100 times brighter than today, because they would have contained many more stars, and they would have been bluer, because the stars would have been about 10 Gyr younger than in today's globular clusters. Also, they would have had similar extensions as today. There would have also been many more such clusters. They may have been more distant, because as our Galaxy became more massive over time, it pulled in its globular clusters. In my research group we are calculating how such clusters evolve, and Dr. Long Wang from China for example, has just joined us as a new Alexander von Humboldt Fellow. He performed the first ever physically fully realistic calculation of a globular cluster with a million stars over a full Hubble time using supercomputers.

Globular cluster M13 in the constellation Hercules

J.Ž.: What is the main reason of their long-term stability?

P.K.: They are stable over many billions of years, because they were born with more than a million stars and the gravitational pull from all the stars on each other is strong. As the clusters age, they loose their stars, one by one, and so the globular clusters we see today must have been born a few to maybe 10 to 100 times more massive than their present day masses.

J.Ž.: How are the stars moving inside the globular cluster and what is the distribution of their velocities?

P.K.: Stars move on smooth but chaotic orbits within the globular clusters. A typical star spends most of its time in the outer regions of the cluster, perhaps 10 light years away from the centre. It then falls though the cluster racing quite rapidly though its inner region to move out again. A typical star moves with about 10 km/s, and the velocity may vary from a few times this amount to nearly zero km/s. At any time, taking all the stars together, the velocities range from near zero to about a few times 10 km/s. About 10 billion years ago all velocity would have been a few times larger, because the clusters were more massive then.

J.Ž.: Do you believe that there are medium-sized black holes inside globular clusters?

P.K.: A scientist should only work with hypotheses rather than have beliefs. So the hypothesis that many globular clusters have massive black holes in them has not been disproven conclusively, and some massive globular clusters could have, near their centres, black holes as massive as a hundred thousand Suns. But there is no theory available today which clearly predicts such black holes to be there. In my research group we are working on this problem, which is directly related to how super-massive black holes form in the centres of galaxies.

J.Ž.: Why do some spiral galaxies have such a perfectly symmetric shape? What is the main reason of this phenomenon?

P.K.: Spiral galaxies, when they are not disturbed, are nearly perfectly round disks. They are, basically, huge accretion disks with radii of up to about 100 thousand light years. Gas falls onto the galaxies at a well defined rate all the time (we neither yet know where this gas comes from nor do we understand why the infall is so well regulated) and, because gas is dissipative, it settles into a rotating disk. In the disk the gas density is higher, and in some places, where it is very high but still much lower than the best vacuum on Earth, the gas clouds fall together because of their self-gravity and stars form. Thus the galaxy evolves by having an increasing number of stars in it, and because it is rotating, it appears round when viewed from the top or bottom, while it is a thin disk when viewed from the side. Such a galaxy remains quite smooth with a huge stellar and gas disk. When it is slightly perturbed, for example, when another galaxy flies past it, even at a large distance, the gravitational pull of the other galaxy changes the forces within the galaxy, and this develops symmetrical spiral patterns. The galaxy reacts to this by becoming a spiral galaxy. This is similar to the Moon tides on the Earth which are also on both sides of the Earth. The spiral pattern in a galaxy is long-lived on human standards. It lasts maybe ten rotation periods, that is, maybe a billion years or more, because once the spiral pattern is there, it might be able to keep itself going through resonances. Additional instabilities may develop. For example, the inner region can form a bar

Some spiral galaxies show a perfectly point-symmetric shape.

in which stars and gas move on more radial orbits. But because disk galaxies are rotating and self-gravitating, they are generally (when not perturbed) symmetrical about their centre.

J.Ž.: What, in your opinion, is the composition of the halo of the Milky Way?

P.K.: The halo of the Milky Way is made up of ancient stars. These stars are as old as the globular clusters, and probably come from them, because the globular clusters loose their stars over time. Many of the halo stars were also formed in much less massive clusters at the same time as the massive present-day globular clusters, which have already lost all their stars long ago. The halo of our Galaxy is the oldest structure. It formed before the Galaxy existed as a spiral galaxy. At that time this birth of our porto-galaxy was extremely violent, with incredibly massive gas clouds falling together into the proto-galaxy and vigorously forming stars in huge star bursts which later became our globular clusters. The gas has today gone a long time ago, probably used up in making the halo stars and the globular clusters, possibly also being driven out of the young Galaxy or fallen into it to make the spiral Galaxy. The halo of the Galaxy is thus mostly without gas. The gas present in it comes from the stellar winds and by falling onto the Galaxy from the outside. That gas is falling onto the Galaxy and this sustains its on-going star formation. If no new gas were falling onto the Galaxy, then it would have consumed its gas many billions of years ago.

J.Ž.: Can you please explain us the notion of gravothermal catastrophe?

P.K.: The gravothermal catastrophe or instability is an interesting phenomenon in self-gravitating stellar-dynamical systems. In a star cluster with sufficiently many stars to live for a sufficiently long time, the following happens: the stars constantly meet each other and pull at each other gravitationally. Even though these pulls are very weak, they cause the stars to slightly change their orbits in the cluster. A star which, for example, is on a circular orbit, will with time change its velocity and begin to move on an eccentric non-circular orbit. As it then falls towards the inner region of the cluster, it becomes faster, passing more stars in a shorter time, and thus allowing it to change the speeds of the other stars. Over time this develops such that some stars end up falling towards the inner most regions, while other stars move out into the outer regions. This is a consequence of energy conservation. The stars falling towards the inner region have the smallest amount of energy, and the stars moving outwards compensate by having the largest energies. The stars form a thermodynamic system in which the fastest stars (the ones in the inner regions) shed some of their energy to the other, slower stars, which absorb this energy and move out of the inner regions. Since a star gets faster the deeper it falls into a gravitational potential, this process has no end. A group of stars can keep on falling inwards, generating ever more negative (binding) energy and a very dense central region in the cluster, while the rest of the cluster expands. This is called the gravothermal instability. It comes about because a self-gravitating system of stars has a negative heat capacity, that is, taking energy out of it makes it hotter. This can be visualized by looking at a satellite of the Earth. If we slow down the satellite, the satellite falls towards the Earth, becoming faster. The more we slow it down, the faster it falls. The same process happens in a cluster of stars. A star, which is slowed down by a gravitational encounter with another star, speeds up as it falls towards the cluster centre. By the principle of energy equipartition, this sped-up star can again share its kinetic energy with other stars, thus becoming even slower, and therefore, speeding up again as it falls towards the centre.

J.Ž.: You are dealing mainly with Newton's theory. Do you think that this theory of gravity sufficiently accurately describes the behavior of spherical clusters and that there is no need to assume the hypothetical nonbaryonic dark matter?

P.K.: When addressing this particular question one needs to understand that Newton derived his universal law of gravitation using data limited to the physical parameters of the Solar System, out to Uranus only. This was published around 1686 while Neptune was discovered about 100 years later. Einstein used this same law as a necessary and required classical limit of his re-interpretation of gravitation in 1916 as a geometrical space-time distortion, because observational data which constrain the law of gravitation were still limited to the Solar System. Galaxies, let alone the dynamics of the Universe, had not been understood in the days of Einstein. Astronomers and physicists extrapolate the empirical laws of gravitation by many orders of magnitude to the scales of star clusters and galaxies. Every school child knows that such extrapolations almost certainly never work. But, on the scales of the normal globular star-clusters, which corresponds to an extrapolation by more than 4 orders of magnitude in spatial scale, the universal law of gravitation as derived by Newton and Einstein largely holds well. That is, the stars are moving, statistically, within the clusters, as is expected that they should be moving. There is no evidence for major departures. Very large departures are seen on the scales of galaxies, which constitute an extrapolation in spatial scale by roughly eight orders of magnitude. Here the observed speeds of stars are too fast, that is, the observed normal matter in stars and gas cannot provide enough gravitational pull (according to the huge extrapolation of Einstein's or Newton's theories) to hold onto the stars. The average physicist and astronomer interprets this to be due to unseen mass, the "dark matter", which provides extra gravitational pull so that the stars and gas move faster (see [1]). A big problem with this explanation is that this additional "dark" matter is not part of the standard model of particle physics. One needs to speculate that the dark matter is made up of particles which are very exotic and do not interact electromagnetically at all so that they remain entirely invisible. But another, and physically more convincing explanation, is that the "universal law of gravitation" as formulated by Newton and reformulated later by Einstein cannot be extrapolated to this extend.

J.Ž.: Einstein's theory of general relativity is examined on relatively small scales. Do you think it is applicable to galactic scales, or to the whole universe?

P.K.: The theory of General Relativity has been found to be in excellent agreement with all available observational data on small scales (i.e. Solar System and smaller) and in gravitational potentials which are deeper than that of the Solar System, that is in space-the curvatures which are larger than found in the Solar System.

J.Ž.: In 2011, the Nobel Prize for Physics was awarded for the discovery of an accelerated expansion of the universe. Did this discovery surprise you?

P.K.: I am in general against the existence of such prizes in the pure sciences, because they corrupt progress. What I mean here is that many institutions are eager to have staff which obtained such and other prizes, and scientists who obtain such prizes have a special status in these institutions and in society. It would be better if scientists achieve recognition, not through prizes, but by naming of some effect after them (e.g. Einstein's theory of general relativity, or Newton's theory of gravitation). My feeling is that too many scientists therefore try to do scientific work which enhances the chances of getting some major prize. But the true aim of a pure scientist should be only and only to try to understand how nature works, irrespective of achieving prizes. Thus, for example, the reason why the scientific community has gone essentially insane on dark matter and dark energy is probably due to this issue, namely that by working well within some conceived main stream which emerged over time, one may enhance ones own chances of getting rewarded. So one can observe how certain young researchers make steep careers by working closely within the main stream ideas and harshly rejecting critical work. This is an in general interesting problem for philosophers to study — how did modern science fail in this way — but concerning the question at hand, the reward of the Nobel Prize in 2011 to Perlmutter, Schmidt and Riess for discovering the accelerated expansion of the Universe, I can state that this discovery is important. Why? Well, the main stream interprets the observations to mean that the Universe is expanding faster than thought, based on the above mentioned extrapolation by a huge order of magnitudes. The main stream scientist had become so overwhelmingly convinced that the extrapolation is correct and the only proper way of doing research, that it came as a surprise that the observations showed a failure of the theory. This failure can be fixed by inventing "dark energy". So the average main stream researcher was convinced that Pearlmutter, Schmidt and Riess made a major discovery of new physics (called dark energy). But this may be an entirely wrong physical explanation, because the extrapolation of physical laws, which were constrained only within the Solar System, as described above, is almost certainly wrong. In truth, it is more likely that the observations organized by Perlmutter, Schmidt and Riess are indicating that the extrapolation is wrong, and that the dynamics of the Universe cannot be described by the Einsteinian/Newtonian formulation as is used by the main stream scientist today. In my research group we are following this path of investigation, that is, we want to learn what these type of observations, as well as many other data, are telling us about the physical theory which governs the gravitational dynamic of galaxies and the Universe. We are explicitly following ideas on gravitation and dynamics which go beyond Newton and Einstein.

J.Ž.: Last year the Nobel Prize for Physics was awarded for the detection of gravitational waves. They were generated by two merging black holes of about thirty Sun's masses. Is the origin of such a system realistic at all?

P.K.: The formation of a binary system composed of two black holes with masses near 30 $M_\odot$ is reasonably well understood today. In my research group, Dr. Sambaran Banerjee, a brilliant researcher from India, is one of the world-wide leaders on this problem. He is calculating how globular star clusters, the stars within which have low-metallicities, evolve over many billions of years. Early-on and within the first 50 million years, the many massive stars die, many leaving black holes. These sink to the centre of the cluster through the above described process of energy equipartition which leads to the gravothermal instability. In the core of the globular cluster, the black holes form binary systems. These binary systems loose energy (thereby becoming more bound) by ejecting stars and other black holes out of the cluster and they can become very compact. Typically, they too are expelled from the cluster after some time, leaving a very tight black hole binary system. Such systems radiate gravitational waves until they merge. They merge in their cluster, or they may merge far away from it. Dr. Banerjee has made many calculations which show that what has been observed is very natural and quite common. In fact, in 2010 we were one of the first to make proper predictions for the type of gravitational events now observed. It may also be possible to make such a binary black hole system only from two massive stars which were born in a binary system. The stars need to be very massive, maybe 100 times as massive as the Sun, and the evolution of this stellar binary needs to be extremely fine-tuned in order for the final black hole binary to survive the huge mass loss from the binary system as the two massive stars evolve and to in the end be so tight as to emit gravitational waves for it to merge to make observed signal. Both lines of research, via the dynamics in star clusters and via stellar evolution, are important and very interesting current hot research topics.

References

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