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CONTRIBUTIONS OF ASTRONOMY TO FUNDAMENTAL PHYSICS

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As the title of this talk indicates, I wish to highlight the valuable contributions astronomy has made towards our understanding of the basic laws of physics. Indeed, the physics-astronomy relationship is a two-way interaction—a fact very often not appreciated by physicists in general, who believe that physics contributes to our understanding of astronomy but not vice versa.

It is true that our understanding of cosmic phenomena requires the knowledge of the laws of physics : the laws that have been conceptualized through numerous laboratory experiments here on the Earth. At the same time, we should remember that the cosmos provides a setting for the operation of these laws that is so grand that it can never be achieved in the terrestrial laboratory.

THE INVERSE SQUARE LAW

Take the law of gravitation, for example. It is said that the falling apple inspired Newton to think of the inverse square law of gravitation. Nothing could be farther from reality. Even the extraordinary genius of Newton would be unable to deduce the law from the observation of the falling apple. Not even the sophisticated instruments of today can make measurements of the falling apple accurately enough to arrive at this law.

The law was arrived at by studying the motions of the moon and the planets. It was Kepler's work of a lifetime that extracted the pattern behind planetary orbits—a pattern that was subsequently explained by Newton's laws. The law of gravitation thus owes its origin to astronomy and not to laboratory physics.

Cosmic phenomena provide fresh testing grounds for science and thus complement the role of the terrestrial laboratory. The only difference is that these events occur far away and beyond the control of the scientist. Otherwise the spirit of enquiry and the application of the scientific method are the same in astronomy as they are elsewhere in science.

How does astronomy contribute to physics? Whenever the physical parameters and their empirical relationships observed in cosmic events receive explanation through the physics we know, we get further reassurance that these

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*At Madurai during the INSA Council and General Meetings.

laws work in those cosmic conditions also. For example, the inverse square law of gravitation derived from planetary data, also applies to binary stars. This circumstance tells us that the law is valid for larger masses at longer distances. A more interesting situation arises when such empirical relationships do not have a ready interpretation.

THE WILSON-BAPPU EFFECT

Let me give an example from Vainu Bappu's work, known as the Wilson-Bappu effect illustrated in Fig. 1. This figure shows on a logarithmic scale the emission line width W_2 of ionized calcium line Ca II plotted against the luminosity of most

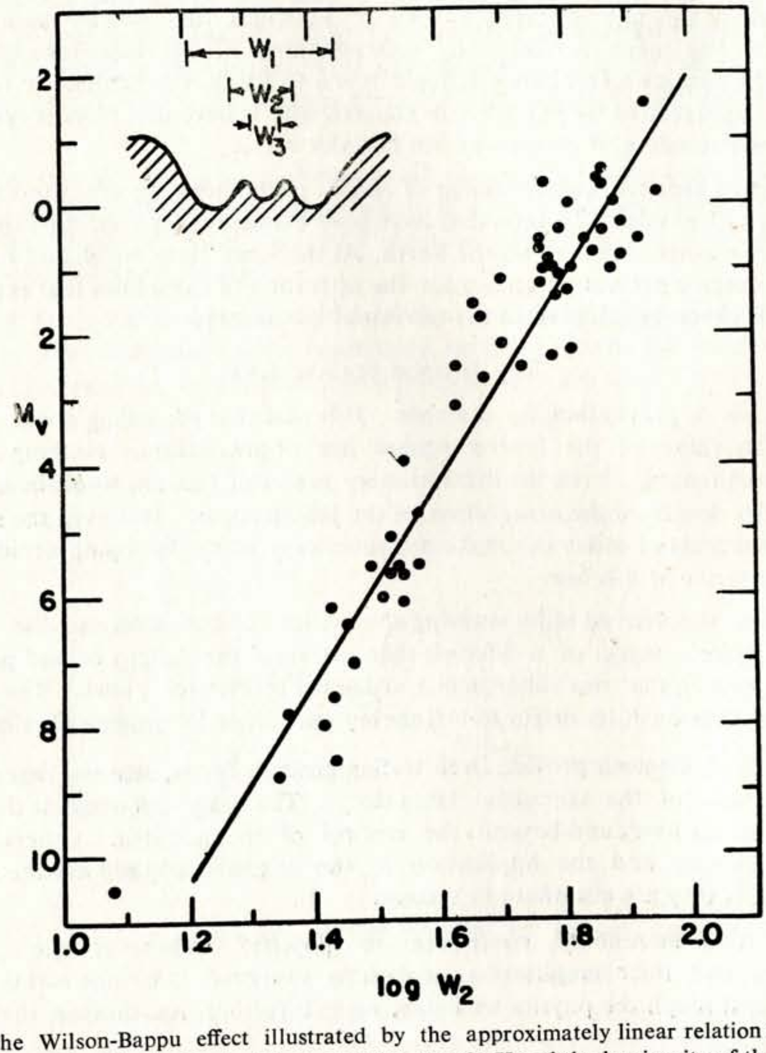

FIG 1 The Wilson-Bappu effect illustrated by the approximately linear relation between the width W_2 of the ionized calcium emission line Ca II and the luminosity of the star, when plotted on logarithmic scales (M_v measures absolute magnitude).

late type stars whose distances are measurable from trigonometric parallaxes. The straight line drawn through the points illustrates the Wilson-Bappu linear law.

Applying this relationship to stars whose luminosities are not known, we can estimate them from the measurements of W_2 in their spectra. From these estimates and from the observed faintness of these stars we can measure their distances. This method has an uncertainty of 10 per cent but is useful if there is no other way of estimating the star's distance.

However, why such a correlation should exist is not yet understood in terms of the underlying physics of stars. I may mention that a somewhat similar effect exists for quasars, discovered by Jack Baldwin. In the Baldwin effect the equivalent width of the C IV λ 1548 line in the spectrum of a quasar is found to be correlated with its luminosity. Again, the underlying physics of quasars cannot as yet explain this relationship.

THE SECRET OF STELLAR ENERGY

Such empirical relationships often serve as starting points on the road to deep physical insights. A success story of this kind began with the empirical relationship shown in Fig. 2. This diagram, based on the early work of E. Hertzsprung and H. N. Russell, and known as the Hertzsprung-Russell diagram (H-R diagram in brief) plots stars according to their surface temperatures on the horizontal axis and luminosities on the vertical axis.

It is noticeable that a lot of stars fall on a band stretching from the lower right end (*B*) to the upper left end (*A*). The stars at the lower end are small, faint, cool, red stars while those at the upper end are massive, bright, hot, blue stars. These adjectives are in comparison with our Sun, shown midway (*S*) on the band. This band is known as the 'Main Sequence'.

Why should stars on the H–R diagram congregate on this band? Why are smaller stars fainter, cooler and redder than the massive ones which are brighter, hotter and bluer? To answer these questions one needs to know what makes the stars shine.

In the 1920s, the Cambridge astronomer A. S. Eddington made a systematic attack on this problem. Treating a star as made of hot ionized gas, Eddington laid down the equations that describe the physics of its interior. One equation describes the relationship of star's mass to its density. Another quantifies the requirement that there is hydrostatic equilibrium between the star's own gravity and its internal pressure. A third equation relates that pressure to the density and temperature within the star. Eddington's fourth and last equation describes how energy generated in the star's central core makes its way outwards through the absorptive envelope.

To complete the solution of the problem, Eddington needed another equation, describing how energy is produced in the star. Here was a stumbling block. What was the mysterious source of stellar energy? Following the suggestion of

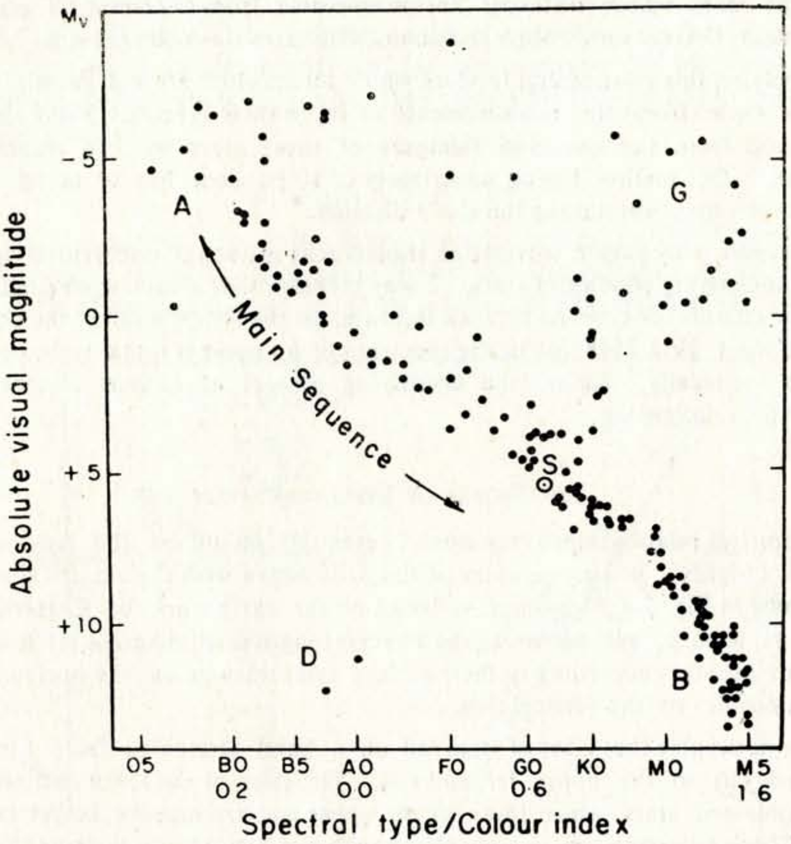

FIG 2 The H-R diagram showing the Main Sequence stars with the Sun (*S*) shown in the middle. The plot shows luminosity against the reciprocal of surface temperature on logarithmic scales. The 'absolute magnitude' and 'spectral type/colour index' are technical astronomical measures of the physical parameters of the stars.

the French astrophysicist J. Perrin, Eddington advocated nuclear fusion as the process releasing energy. The fusion reaction combining four hydrogen nuclei into a helium nucleus results in a decrease of mass. This decrease has to be compensated for by the release of energy according to Einstein's celebrated equation $E = Mc^2$. Eddington had estimated that the central temperature within a star like the Sun would exceed 10^7 K, and at such temperatures the above fusion process should take place.

It was at this point that Eddington had a clash with the nuclear physicists who argued that even these temperatures were not high enough to bring positively charged H-nuclei across the repulsive Coulomb barrier to collide and fuse together. Eddington was adamant, however, in his belief that the very fact that the stars are shining was ample proof of the existence of nuclear fusion. To his critics he had this to say :

"We do not argue with the critic who tells us that the stars are not hot enough for this purpose. We tell him to go find a hotter place."

A decade later, Eddington was proved right. By then the attractive and short range nature of the nuclear force had become better understood and it became clear that nuclear fusion can indeed take place at the temperatures Eddington had calculated. Hans Bethe was able to calculate the complete solution of the equations of stellar structure including the fifth elusive equation.

The solution enables the astrophysicist to express both the luminosity L and surface temperature T of the star as functions of its mass M. Therefore as we vary M, we get a range of (L, T) values along a curve that is none other than the Main Sequence. Thus we are able to understand the band of stars in Fig. 2.

This episode illustrates the two-way interaction between physics and astronomy. The five physics-based equations are able to explain the Main Sequence and provide an answer to the age old mystery of why do the Sun and the stars shine. More importantly, we see here the lead for the idea of nuclear fusion coming from astronomy. Even today, stars are the only sites known where controlled nuclear fusion is going on. To achieve this process in a terrestrial laboratory has not yet been possible.

THE TRIPLE-ALPHA REACTION

There is another example in the area of stellar structures where an astrophysicist's conjecture prompted a successful laboratory search in nuclear structure. This example refers to stars whose nuclear fuel in the form of hydrogen nuclei is all fused up. What happens to such stars?

According to Eddington's equations, a switch off in the energy supply would lead to a lowering of temperature and pressure in the star's inner core and hence its contraction due to self-gravitation. A contracting core of gas, however, heats up. Would this rise in temperature cause the star to stabilize?

Not by itself; but if another exothermic nuclear fusion process takes over at these higher temperatures its energy release could sustain the star for a while. The difficulty arises in seeing what reaction that could be.

For, given a material containing helium (atomic weight 4) and hydrogen (atomic weight 1), further fusion with helium could give nuclei of atomic weights 5 $(= 4 + 1)$ or $8(= 4 + 4)$. Both these nuclei are, however, unstable and split back into smaller ones. The idea of combining three helium nuclei to make a carbon nucleus (atomic weight 12) did hold out a possibility but not a plausible one. For, the chance of these nuclei coming together in a random encounter is relatively small.

At this stage, Fred Hoyle, another Cambridge astrophysicist made the remarkable conjecture that the rarity of a three-body encounter could be compensated for by a *resonant* reaction which proceeds fast. Hoyle calculated that there should be an excited state of the carbon nucleus to which this triple fusion reaction would proceed. Later this excited state would decay to the more common stable state. Hoyle therefore suggested that the nuclear physicists look for and confirm the existence of this excited state.

Hoyle strongly believed that such a state has to exist, for two reasons. First there exist quite a few stars that are not on the Main Sequence. Fig. 3 illustrates the H–R diagram of a star cluster wherein most stars are to the right of the Main Sequence. These are giant stars which are luminous, cool and red. They seem to branch off from the Main Sequence suggesting that they have evolved further, i.e., after the hydrogen fusion is over. Clearly therefore, further fusion reactions must go on within such stars.

Hoyle's second reason was based on his belief that all chemical elements are made in thermonuclear reactions within stars. Thus heavier elements like carbon, oxygen, neon, silicon, iron etc. found in the universe have to come from further fusion processes in stars. Hence, the triple-alpha process* was a logical channel for these processes to follow.

Nuclear physicists were skeptical at first. However, Ward Whaling and others at Caltech did look for the excited state of the carbon nucleus and found

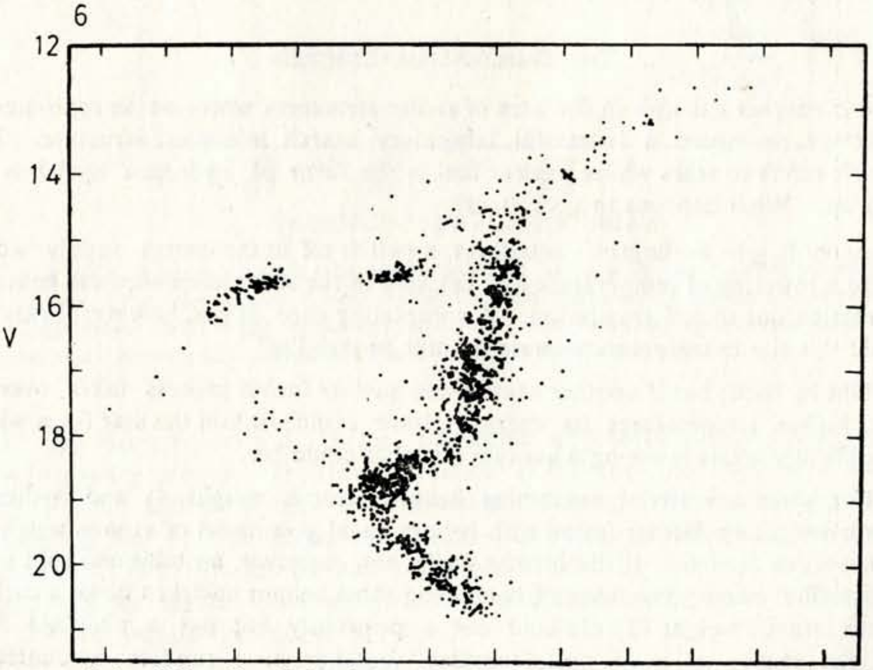

Fig 3 The H-R diagram for the globular cluster of stars M-3 showing the giant stars branching out to the right from the Main Sequence.

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*so called because a helium nucleus is also known as an alpha particle.

it as predicted. A discovery in nuclear structure was thus made from a purely astronomical motivation.

DARK MATTER

Although astronomy deals with cosmic sources of light (and other forms of radiation) it is also concerned with non-luminous matter. Before coming to modern times let me recall the circumstances that led to the discovery of the planet Neptune.

In the first few decades of the nineteenth century the motion of planet Uranus had shown certain irregularities. Either Newton's laws of motion and gravitation were inadequate to explain the observed discrepancies or something was missing from the overall observed picture. U. J. J. Leverrier in Paris and J.C. Adams in Cambridge both independently arrived at the conclusion that there was an extra, hitherto unknown planet in the vicinity of Uranus, causing these perturbations. From their calculations (based on Newton's laws) they predicted the location of the new planet. The planet was looked for and soon found by J. G. Galle of the Berlin Observatory in 1846.

Thus unseen matter can be detected from its gravitational interaction. In the case of Neptune, the unseen planet did become visible when specially searched for. There are other situations in astronomy where the gravitating matter cannot be seen. The probable location of a black hole in Cygnus X-1, an X-ray source is inferred from its gravitational effects. Fig 4 illustrates the scenario.

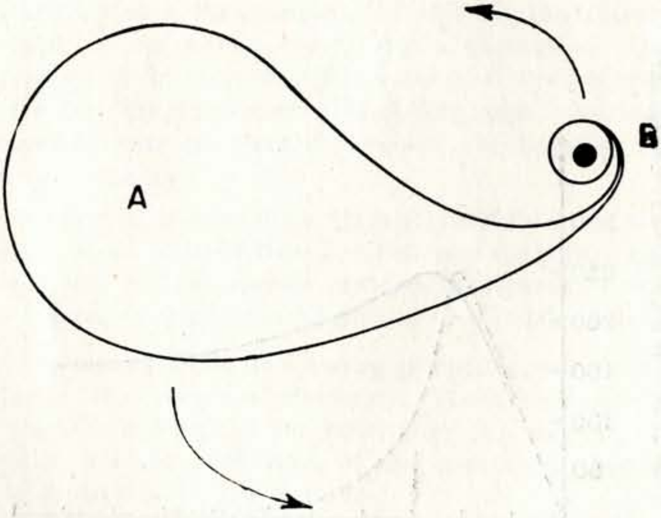

FIG 4 In a typical binary X-ray source an extended star (A) and a compact star (B) revolve round each other. The latter pulls matter away from the former by tidal gravitational force. The matter revolves round B before falling in. The revolving matter forms a hot disc that radiates X-rays. In the case of Cygnus X-1 the star B is compact and massive enough to be considered a black hole, although in most other such cases it is a neutron star.

Dark matter is similarly inferred in galaxies on the basis of the so-called rotation curves. The measurements of radial velocities of clouds of neutral hydrogen (by using the 21cm wavelength) show that these clouds are moving round the galactic centre with velocities that are almost constant over large distances. Fig. 5 illustrates the typical rotation velocity curve by a continuous line.

Why do the clouds go round? Their motion is similar to that of planets round the Sun. In their case the source of gravitational attraction is the matter encompassed by their orbits. If Newton's laws are valid, the rotation curve of Fig. 5 implies that the mass M contained in a sphere of radius R (concentric with the centre of the galaxy) is proportional to R.

This conclusion requires matter in the galaxy to exist out to distances far beyond its luminous boundary. Had the gravitating matter been solely the visible matter contained in the observed boundry, the rotation curve would have shown a dropping tendency as it moves away from the galactic centre, like the dotted curve of Fig. 5.

This discrepancy is very common and can be interpreted in two ways. The first conclusion could be that Newton's laws of motion and gravitation do not work on the galactic scale. They have to be modified suitably to be able to generate the observed rotation curves.

The second alternative, accepted by most astrophysicists, is that there is dark matter around. There are severe constraints, however, on what it could be composed of. Alternatives range from black holes or very low mass stars on the astro-

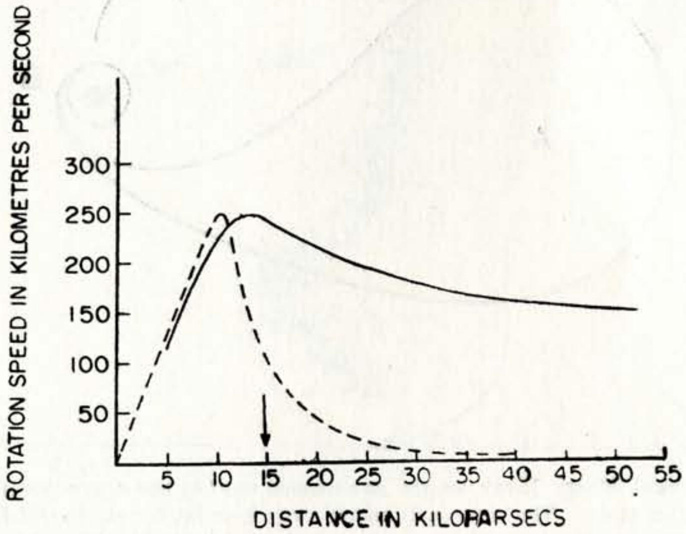

FIG 5 The rotation curve of a typical spiral galaxy extends well beyond its visible boundary shown by a vertical arrow. The dotted curve shows how the rotation curve should fall off if the galaxy only contained visible matter and if Newton's laws are valid.

nomer's menu to a host of esoteric particles like massive neutrinos, photinos, gravitinos, axions etc. speculated on by the particle theorists.

It is too early to say which alternative will hold. In either case astronomy will have provided new inputs to physics. In the first case the laws of gravitation and/or motion will have to be revised, in the other we have evidence for new kind of matter.

ANOMALOUS REDSHIFTS

I end this lecture with some astronomical observations of the Extragalactic Universe that are disturbing, if true. Disturbing, if one wants to hold on to the well-accepted theory of the expanding universe. The observations relate to redshifts of galaxies and quasars.

According to the conventional theory any extragalactic object should show a redshift in its spectrum (i.e., a systematic shift in the spectral lines towards the red end). Moreover, the amount of shift should be uniquely fixed by the distance of the object from us. This is Hubble's law, originally found by E.P. Hubble as a linear redshift distance relation back in 1929 (*see* Fig. 6). The linear relation gets slightly modified at larger distances depending on the geometry of spacetime. The validity of this relation is essential for the expending universe models based on Einstein's general theory of relativity.

It follows from this relation therefore that any two extragalactic objects in close proximity to each other should show the same redshift. Over the last two decades, however, several discrepant cases have come to light where near neighbours show markedly different redshifts. H.C. Arp has played a leading role in turning up such data.

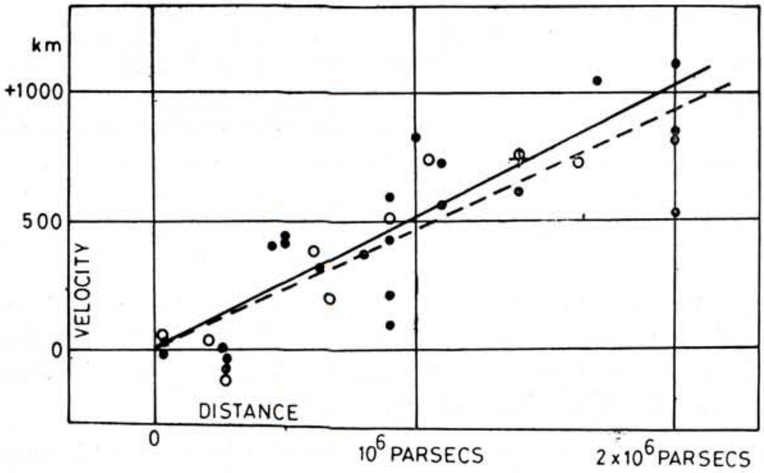

FIG 6 The redshift distance curve based on Hubble's 1929 data. A parsec is approximately 3 light years. The redshifts are given in terms of speeds of recession as interpreted by the Doppler effect.

FIG 7 Three quasars with large redshifts ($z = 1.94, 0.60$ and 1.40) grouped round a galaxy of low redshift ($z = 0.004$). The galaxy is NGC 1073. (Photo from *Quasars, Redshifts and Controversies* by H.C. Arp, Berkeley, Interstellar, Media, 1987).

In Figs. 7–9 we show examples of such anomalous groups involving quasars and galaxies in close proximity with different redshifts. In figs. 8 and 9 there appear to be visible filamentary connections while in Fig. 7 the small angular separation is considered indicative of physical nearness.

Naturally such cases should be, and are, examined very critically since a good deal hinges on them. Are the connections of Figs. 8 and 9 real or artifacts? If real, do they actually connect the two objects? Is the angular nearness of Fig. 7 due to chance projection?

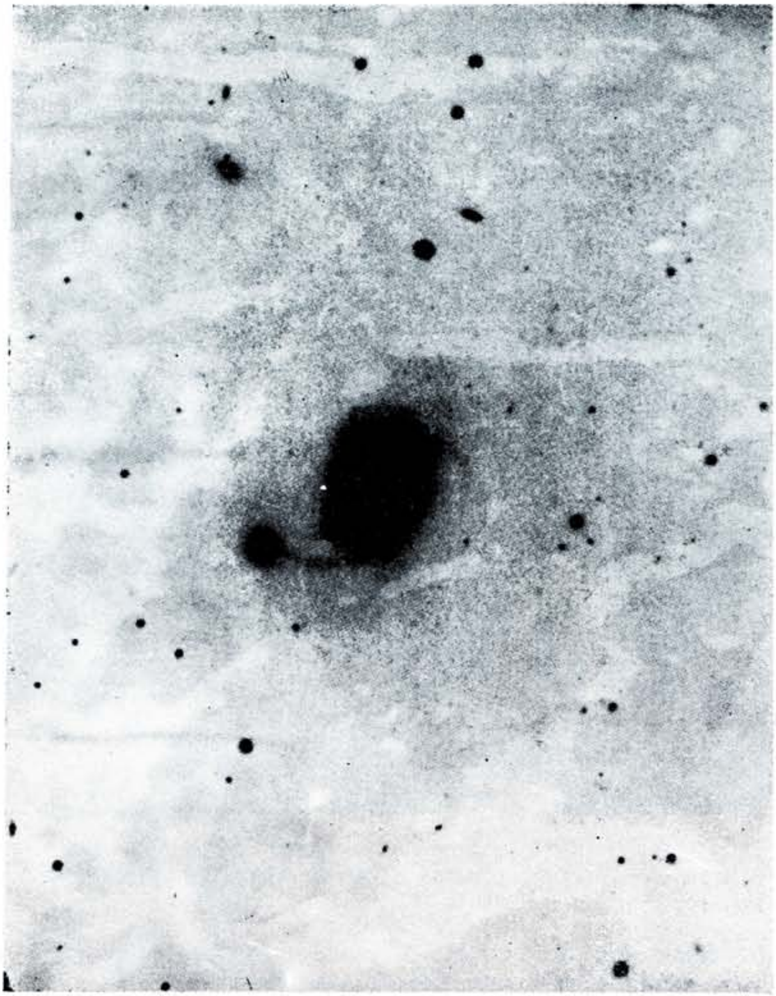

FIG 8 Filament linking a large galaxy (NGC 7603) of redshift $z = 0.029$ to a companions galaxy of a much larger redshift, $z = 0.056$, (Photo from the same source as that of Fig. 7).

At present the issue is controversial but the accumulation of discrepant cases cannot be ignored much longer. If they are real, how do we account for them?

Apart from the expending universe hypothesis, two other sources of redshift are known : the Doppler and the gravitational. Even they do not seem entirely capable of accounting for the discrepant data. In that case, do we need 'new physics'?

For example, the conformal theory of gravity based on Mach's principle, proposed by Fred Hoyle and the author seems capable of explaining the type of observations shown in Figs. 7-9, although it needs to be explored further. This theory may also contain explanation of the so-called 'quantized redshift effect' observed by W. Tifft.

FIG 9 Isophotal contours showing the connection between the galaxy NGC 4319 of low redshift 0.0056 and a quasar like object Markarian 205 of much higher redshift 0.07. (Photo from the same source as that of Fig 7).

Tifft has found that the redshift differences in certain binary galaxies as well as groups of galaxies in our neighbourhood appear (when multiplied by the speed of light) to be concentrated in multiples of 72 km s^{-1}. Several other observers have observed this effect which has so far withstood close statistical scrutiny. Again, the theoretical framework of conventional physics fails to account for these results.

A peculiar situation exists in this field so far as discrepant observations and new physical theories are concerned. Many impartial observers do not take the discrepant observations seriously because they are not aware of any theories that could account for them. (In many cases such theories do exist.) On the other hand many theoreticians do not feel the urge to consider new theories because they are not aware of observations that are discrepant with regard to established theories. (As we saw, such observations also exist.)

CONCLUSION

These examples illustrate the wealth of new information that astronomy is capable of providing. It is but natural that at first sight many cosmic phenomena appear to defy the established physical laws. In some cases, with suitable ingenuity on the part of the theoretician, known physics can account for them. In others it may happen that new inputs to known physics are needed. After all the law of gravitation and thermonuclear fusion are examples of new inputs from astronomy to physics.

Anomalous cases remain unexplained until new theoretical ideas catch up with them. The Fraunhofer lines discovered in 1814 could not be understood until nearly a century later when the quantum theory came on the scene. It is very likely that some of today's puzzles of extragalactic astronomy may be solved by the physics of tomorrow.