Lyman Spitzer: Life, Times, and Science

Rajaram Nityananda

Lyman Spitzer was one of the major figures of twentieth century theoretical astrophysics. Over more than fifty years, he kept up sustained research of his own, on problems concerning the interstellar medium, star formation, and galaxies. In addition he was a major influence on observational programmes, and created a thriving school of theoretical astrophysics at Princeton University along with a strong plasma physics programme. This article brings out his contributions, placing them in context.

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Lyman Spitzer Jr. was born in 1914 and raised in a small town, Toledo, Ohio. Since he bore the same first name as his father, Jr. for Junior was added. His early education was in the same town, but he moved to Massachusetts for high school, where his interest in physics and astronomy was first kindled. His bachelors degree in physics which he obtained with distinction, was from Yale University. He then won a one year Fellowship to St. Johns College, Cambridge, in the academic year 1935–36. It was common in those days for promising students from the United States to spend some time in England or Europe – the precise opposite of the situation today!

Cambridge exposed Spitzer to the most distinguished astrophysicist of that time – Arthur Eddington. This was something of an accident, given that his initial intention was to do theoretical nuclear physics with R H Fowler. Although Eddington was a rather senior and reclusive figure, and they did not meet often, his style of using physics to understand the cosmos, and his masterly writings, made a deep impression on Spitzer. Equally significant was overlap with Subrahmanyan Chandrasekhar[1] who was four years his senior. He has recorded his admiration for the elegant lectures on stellar structure which Chandra delivered to a small group, and this connection remained over the years. The Cambridge stay

[1] *Resonance*, Vol.2, No.4, 1997.

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turned him decidedly towards the stars, and to Princeton University, where the Astronomy Department and the Observatory was headed by H N Russell, a pioneering astronomer of United States at that time.

Russell is known to all the students of astronomy for a famous diagram which he proposed in 1913, independently of E Hertzprung in Europe two years earlier. In this diagram, each star is placed according to its luminosity and temperature, and it is absolutely fundamental to stellar astrophysics. Russell is also known to students of atomic physics for the Russell–Saunders coupling, which describes the interaction between the spin angular momentum and the orbital angular momentum of electrons in atoms. Spectroscopy was a major theme with astrophysicists then – as now. Spitzer recalls this association with much respect but his research was largely on his own, on the atmospheres of giant stars, based on newly obtained spectra to which Russell had access. Spitzer was not closely associated with the observatory, and took his preparatory courses in theoretical physics, an area in which Princeton University was – and is – very strong.

His postdoctoral stay was in Harvard observatory, which was presided over by H Shapley, with a galaxy of distinguished colleagues and visitors. The elucidation of nuclear fusion as the energy source of stars by Hans Bethe[2] was fresh. It immediately led the young Spitzer to the realisation that the hottest, brightest stars live for rather short periods, just tens of millions of years, after which they run out of fuel. Since we see them now, they must be continually replenished in our Galaxy which is much older. This conclusion, which seems so obvious today, but was not appreciated at that time, led to his lifelong interest in the formation of stars, and the material out of which stars formed – the interstellar medium. This side of Spitzer's work is explained in Biman Nath's article (Gas Between the Stars: What determines its temperature?) in this issue (pp.985–996). It is reflected in the title of three of his books – *Diffuse matter in space*, *Searching between the stars*, and *Physical processes in the interstellar medium*. It also led him to consider how the birth and death of stars would

[2] *Resonance*, Vol.10, No.10, 2005.

affect the observed properties of galaxies as a whole, a topic on which he wrote three papers in this period.

The seed of another major interest was planted in Harvard, in a discussion of globular clusters (*Figure* 1). These are systems of upto a million stars, occupying a region of size about 100 light years, but with a dense central core only a few light years in size. It was already known that these are bound systems, with the kinetic energy of movement of the stars equal to half the gravitational binding energy. (This is the so called 'virial theorem', valid for inverse square forces, and hence equally for molecules made up of protons and electrons, and for galaxies!) It was also known that over the timescale of millions of years, random close encounters between pairs of stars would allow them to exchange energy, driving them to a Maxwellian distribution of velocities, just as in a laboratory gas. However there was a theoretical problem – a model with spherical symmetry and such a thermal equilibrium distribution would have no boundary and infinite mass. Spitzer came up with the solution. Globular clusters were finite and not truly in equilibrium – high velocity stars would escape from the system. There is a similar process in the Earth's own atmosphere – with lighter, higher velocity molecules like hydrogen and helium escaping. He worked out the astronomical consequences of this 'evaporation', not knowing that two years earlier, in 1938, V Ambartsumian the Russian/ Armenian astrophysicist had done

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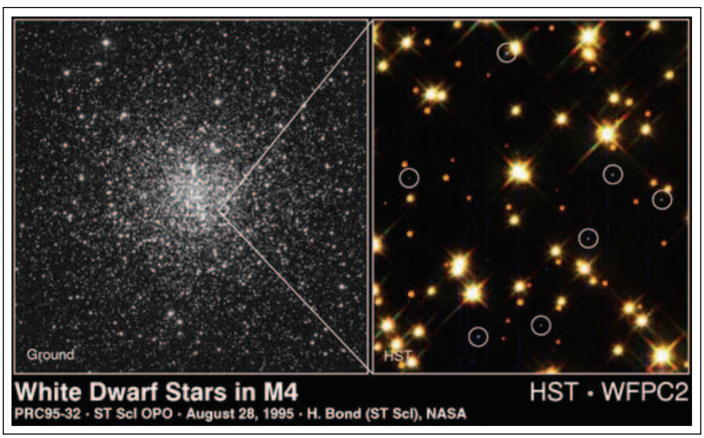

Figure 1. Globular cluster M4, as seen from the ground, and a small part seen in detail by the Hubble space telescope (Image credit: H.Bond, STSci).

precisely this. As Spitzer remarked later, when he learnt of the earlier work, he was relieved that their main results agreed – he was never one for conflicts over priority.

"Would you be interested," he asked me, "in writing a chapter on how such a satellite might be useful in astronomy?" With my long and ardent background in science fiction, I found this invitation an exciting one and accepted with great enthusiasm.

After a year of postdoctoral work, Spitzer was offered a position at Yale University in the Physics Department. His Yale period was interrupted by four years of work for the US Navy on the underwater propagation of sound. This is of interest both to detect enemy submarines and to avoid one's own submarines being detected. The role was more managerial – travelling to the different centres, understanding and if need be critically reviewing what was being done, and helping with its translation into terms which made sense to the Navy. The end of the war had another consequence – awareness of German rocket technology in the United States. A secret group was formed to look into its implications. As Spitzer recollects,

"As World War II drew to its end, I was approached by a friend on the staff of the RAND corporation, an Air Force 'think-tank'. He told me that his group was carrying out a secret study of a possible large artificial satellite to circle the earth a few hundred miles up. "Would you be interested," he asked me, "in writing a chapter on how such a satellite might be useful in astronomy?" With my long and ardent background in science fiction, I found this invitation an exciting one and accepted with great enthusiasm."

The result was a paper which is now regarded as the genesis of the Hubble Space Telescope, which revolutionised astronomy after 1989 and is still functional.

It must have seemed like science fiction in 1946, when the first artificial satellite was still eleven years into the future. His prescient article is reproduced in the Classics section of this issue (pp.1047–1059).

This period also saw the start of a major partnership with the astrophysicist Martin Schwarzschild which lasted for half a century, through their entire future careers. The year 1947 saw a move from Yale University back to Princeton, but now as the replacement for the same H N Russell who had been his mentor ten years earlier. The confidence with which a 33 year old approached this prospect is reflected in the following extract from his correspondence with the University.

My own respect for the astronomy at Princeton in general and for Professor Russell in particular, is so profound that it would be a great personal pleasure for me to come to Princeton under almost any conditions.

"*For many reasons, I believe that the chairmanship at Princeton offers very great opportunities of the sort which interest me, and I would definitely accept an offer from Princeton University if it were along the lines which I visualise, and which I describe below ... The most important aspect of the Princeton opening, from my point of view, is the general policy of the University administration towards the Astronomy Department. My own respect for the astronomy at Princeton in general and for Professor Russell in particular, is so profound that it would be a great personal pleasure for me to come to Princeton under almost any conditions. The very strong support which astrophysics enjoys at Yale, however, would make it very difficult for me to leave New Haven with its effective opportunities for effective research and growth unless the corresponding opportunities at Princeton are at least as great.*"

It is now history that Spitzer was offered the chair, with major support from Shapley in Harvard. But only after the position had been first turned down by Chandrasekhar; the President of the University of Chicago had to intervene to retain Chandra who was seriously interested! Spitzer spent the rest of his life working in Princeton. His very first act was to bring in Martin Schwarzschild as an associate professor. Between them, they changed the face of astrophysics at the University. Existing programmes on binary stars with the small on-campus telescope – a favourite theme with Russell, were gracefully eased out. A standing agreement allowed Princeton astronomers – professors and students, to spend one fourth of their time with the great observatories of the West Coast of the United States, such as Mount Wilson, fully funded by the University. A galaxy of eminent visitors would pass through, as well as young postdoctoral fellows. The foundation was laid for a formal graduate programme. The tradition that students entering this programme do a few different research projects with the professors before they can start their PhD, continues to this

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day. Spitzer was able to obtain independent funding for many of these activities.

In the 1950s and later, he returned to the theme of globular cluster dynamics which he had opened up in his 1940 paper. Two basic processes driving the approach to a kind of thermal equilibrium had already been identified and quantified by Chandrasekhar in a series of papers, a book *Stellar dynamics* and in a major article in the *Reviews of modern physics*. In a nutshell, these are as follows. If a star were to start with zero velocity, random encounters would give it a velocity, average magnitude growing with time, but with a random direction. This is known as diffusion in velocity space (See *Box* 1). Clearly, there must be a balancing process to respect conservation of energy. This is called 'dynamical friction' – a term introduced by Chandrasekhar, and which is best appreciated in the extreme case of a star moving much faster than its surroundings. In its frame of reference, it sees an almost parallel beam of oncoming stars. This beam is focused by the gravity of our test star, giving excess density behind it. (*Figure* A) The net effect is to reduce its velocity towards the average (with momentum conservation of course). Precisely these two processes had been identified long ago in the theory of Brownian motion, where the 'friction' is nothing but the viscosity of the liquid surrounding the particle which is also ultimately dynamical in origin.

The stellar case is more complex because both these processes depend on the velocity of the test star as well as the entire distribution of velocities of the other stars. Technically, one has to solve a non-linear integrodifferential equation. This had just become possible thanks to the advent of digital computers in the 1960s. With a series of PhD students, Spitzer went on step by step to make quantitative calculations of the consequences for the evolution of a cluster. Apart from evaporation, already mentioned, this group worked on two more effects.

One is the 'mass segregation instability' – the tendency of heavier stars to 'sink' towards the centre of the cluster.

Box 1. Velocity Space Diffusion and Dynamical Friction

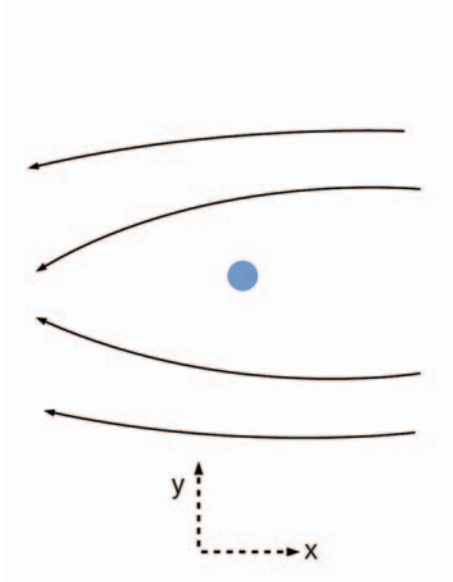

Figure A. An encounter between a test star (blue circle) moving at a high speed along the x-axis through a population of field stars. The encounter is sketched in the frame of the test star. It is assumed to be heavy, so taken as fixed, only for simplicity. The field stars appear to come from a single direction, opposite to the motion of the test star. Four unbound (i.e., hyperbolic) orbits are shown, bringing out the larger deflection when they pass closer to the test star. The excess density at the back is responsible for transferring momentum along x-axis to the test star, One can see that the x-component of the momentum of the field stars, which starts out negative, reduces in magnitude as it should from conservation. This represents dynamical friction. The transfers of momentum along the y-axis (and z, not shown) cancel out, on the average. However, because of the random signs, a residual mean square transfer occurs along y and z (and also along x, after removing the average). This represents velocity space diffusion.

The quotes are because this is not a steady downward journey but a slight bias in the collisions which ultimately results in a shrinking of the orbit. At some stage, this can become a runaway process. The deepening of the potential well due to the entry of more massive stars into the central regions increases the tendency for those stars to continue their inward migration at an increasing rate.

The second was the 'gravothermal instability', which was discovered by Antonov in Leningrad. Antonov's work was unfor-

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tunately missed by the Western community, so it had to be rediscovered by Lynden-Bell and Wood. This is a process whereby a 'temperature gradient' develops spontaneously. An oversimplified description would be evaporation from the centre of the cluster to its outer parts, rather than to infinity, with consequent shrinkage of the core. This substantial body of work was also driven by new and improved observations. One major ingredient in our picture today, pioneered by Heggie in England is the formation of binaries, and their effect on other stars. Collisions with a third star can now act as a 'heat source' since the binary star can become more tightly bound. All this was summed up in a book *Dynamical Evolution of Globular Clusters* which Spitzer authored in 1989. Of course, the subject has progressed greatly since then, but the fundamental physical principles remain unchanged.

[3] Biman Nath, Jan Hendrik Oort – A Complete Astronomer *Resonance*, Vol.20, No.10, pp.864–865, 2015.

We must mention some more pieces of work from this period, because they are now part of standard astrophysics textbooks. One, proposed with Oort[3] is a mechanism for accelerating clouds of interstellar gas by the effect of stars heating them from one side. The hot gas emerges asymmetrically and acts like a rocket exhaust, propelling the cloud in the opposite direction.

Another important work with Schwarzschild was motivated by the observation that older stars seemed to have higher random velocities. This was attributed to the random acceleration of stars by encounters with irregularities in the gravitational potential. These could be caused by giant gas clouds or spiral arms of galaxies, and variants of this explanation continue to be used today.

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A third problem needed an excursion into solid state physics! Interstellar space is filled with what are called dust grains – particles mostly less than a micron in size made of graphite or silicate. Interestingly, the pollution in our cities consists of similar materials – carbon from automobile exhausts and fine silicate particles from the construction activity!. For more on this fascinating area, see 'Dust in space' by Biman Nath (*Resonance*, Vol.8, No.1, pp.15–29, 2003). One of the unexpected discoveries of the 1950s was that the dust grains in interstellar space had a preferred orientation, as shown by the different absorption of the two polarisations of light. It was no surprise that the grains, built up by random processes, were not spherical in shape. But what would define the preferred direction? It had to be the interstellar magnetic field, which had been proposed by Fermi[4] and Chandrasekhar some years earlier. Davis and Greenstein proposed an ingenious mechanism which involved excitation of the rotation of the dust grains by collisions with hotter gas, and dissipation of this rotational energy. Spitzer's follow up with Jones brought out the importance of the gas and dust temperatures being unequal, and the role of the magnetic properties of the grains, which presumably contained some iron.

[4] *Resonance*, Vol.19, No.1, 2014.

Yet another basic dynamical process which Spitzer worked out was the consequence of two galaxies colliding with each other. This does not imply physical collisions between the stars. Even the pairwise gravitational scattering which we described in the context of globular clusters is negligible. The main effect occurs because the mean potential in which the stars move in each galaxy is now seriously disturbed by the proximity of the other. To make matters worse, this potential depends on time, posing a rather complex problem. Spitzer cut this Gordian knot by considering a limiting case when the two galaxies were spheres, and their relative velocity was very high. The entire interaction then lasts for a time short compared to the orbits of stars in the individual galaxies. In this case, one can think of each star in a given galaxy as receiving an impulsive change of momentum, which is not hard to calculate, from the time dependent potential from the other galaxy. The result is that some of the kinetic energy of relative motion of the two galaxies is converted into the internal energy of the two galaxies. Further, the two galaxies would need to readjust to a new equilibrium after the encouter was over. This extreme case then guided much later work.

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The original motive was to explain the so called lenticular galaxies (*Figure* 2). This has not stood the test of time. However, the idea of inelastic interactions has come to stay – in extreme cases, the two galaxies are not able to escape to infinity after the loss

Figure 2. NGC3115, an example of a lenticular galaxy.
(Image credit: 2MASS (Two Micron All Sky Survey))

of their relative kinetic energy and they merge. The impulse approximation of course completely fails in this regime and more quantitative work had to wait for numerical simulations. with large computers. Mergers and acquisitions among galaxies are very much part of modern cosmology. As in many other areas, Spitzer was a pioneer, showing the way to others.

While these appear to be isolated interesting problems, the long term programme of understanding the gas between the stars and the formation of stars was never far from his mind. In his scientific autobiography, *Searching between the stars*, Spitzer gave a personal account of his own favourite moment – the successful launch of 'Copernicus' a space mission to study the ultraviolet spectra of stars. These reveal information simply not accessible from the ground because of the absorption of short wavelengths in the Earth's atmosphere. In particular, the spectra reveal the presence of five times ionised oxygen in the interstellar medium, evidence for a high temperature component. The data from this satellite proved to be a mine of information about hot stars and

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the gas absorbing their radiation on its way to Earth. One interesting sidelight is that shortly before the launch, Spitzer calculated the effect of zero gravity on the telescope, which had been designed and assembled by engineers in the Earth's gravity. It turned out that the dimensions would have changed slightly, but enough to degrade the optical performance. Fortunately, the required correction could be applied before the launch! His passion for physical processes was not confined to the heavens.

This brings us to his other great dream, of harnessing the same fusion reactions which power the stars for energy production on earth. To achieve this, one needs to heat and confine gas at high enough temperatures to produce fusion in a controlled way. The thermonuclear (also called hydrogen) bomb had already demonstrated uncontrolled nuclear fusion by 1950. One approach was to have a plasma – a fully ionised gas – of deuterium, which undergoes fusion at lower temperatures than hydrogen, at about 100 million degrees. The charged nuclei and electrons at high temperature need to be kept in a container without touching the walls, and this is achieved by magnetic fields. It is well known that charged particles orbit in circles in a plane perpendicular to a uniform magnetic field, while the centre of the circle moves uniformly along the field. However, a laboratory device cannot have an infinite uniform field, so one configuration which is often used is a torus.

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Orbits in a non-uniform, curved field, pose an interesting challenge to the theorist, but an experimenter would regard them as a nuisance since they spoil the confinement of the plasma. Spitzer invented a rather complex field configuration with twisted lines of force which overcame many of these difficulties, and he called it the 'stellarator'(*Figure* 3). Under his leadership, a plasma physics laboratory was established in Princeton, which he headed for 15 years. His lectures became another classic book *Physics of fully ionised gases*. His globular cluster work stood him in good stead. The physics of collisions in a high temperature plasma is governed by inverse square forces, though, unlike gravity, of both signs. His formulae for the resistivity and thermal conduction in

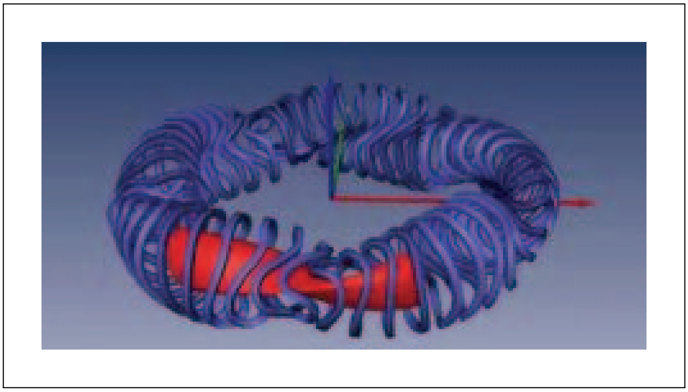

Figure 3. The stellarator. The magnetic coils (blue) and plasma (red) in a diagram showing the geometry of a modern stellarator.
Credit: Max Planck Institute of Plasma Physics.

such a plasma without boundaries are reminiscent of the formulae for the relaxation time in star clusters. They have now become standard in the plasma physics literature. It must be mentioned that laboratory plasmas are usually much smaller than the mean free path, so this theory is not directly applicable. Although modern versions of the stellarator exist, most of the world effort in plasma fusion is based on another concept, the 'tokamak' (The name was given by the Russian scientists Tamm and Sakharov). The tokamak is geometrically much simpler than the stellarator, but needs a strong current flowing in the plasma to achieve the same twisting effect – at the price of many other instabilities which have to be controlled.

I cannot resist closing with a small first hand account of Spitzer in his later years. For five months in 1983–84, I had the privilege of visiting the Department of Astrophysical Sciences at Princeton University. The faculty offices had glass walls looking to the outside. One could see the lights on and Spitzers figure at his desk, late in the evening when much of the building was empty and most of the occupants had gone home, even though he had 'retired' in 1979! He moved freely with the research students, to whom he was 'Lyman' and sometimes a companion in mountaineering. (The word 'Spitz' can mean a mountain peak in German). He took regular part in discussions over tea and lunch, in a deceptively mild manner – his views were taken very seriously!

Spitzer and Schwarzschild both passed away in 1997, within two weeks of each other. The joint obituary I wrote for *Current Science* concludes "*It would be hard to find, anywhere, examples of academic retirement so filled with grace and purposeful activity and the respect which it engenders. The Indian tradition describes the ideal of a 'sanyasi' – an older person who sheds all desires, living in the middle of the world but apart from it, carrying out his duties and sharing his wisdom with younger people in a spirit of detachment. In faraway Princeton, I was fortunate to see two people who exemplified this spirit.*"

Spitzer passed away on March 31 1997. He had started work as usual on that morning, with some data from the Hubble Space Telescope! NASA launched an infrared telescope in 2003, This revealed many new things about interstellar dust and galaxies (see cover picture) . Fittingly, it was named after Lyman Spitzer.

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Suggested Reading

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[2] Lyman Spitzer Jr., *Searching between the stars*, Yale University Press, 1982.

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