Astrophysics

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During the 100 years that astrophysics has been recognized as a separate discipline, there has been progress in interpreting observations of stars and galaxies using the principles of modern physics. Here we review some of the highlights, including the evolution of stars driven by nuclear reactions in their interiors, the emission of detectable neutrinos by the sun and by a supernova, the rapid and extremely regular rotation of neutron stars, and the accretion of matter onto black holes. A comparison of the observed Universe with the predictions of general relativity is also given. [S0034-6861(99)04602-4]

I. INTRODUCTION

Astrophysics interprets astronomical observations of stars and galaxies in terms of physical models. During this century new classes of objects were discovered by astronomers as novel instruments became available, challenging theoretical interpretation.

Until the 1940s, astronomical data came entirely from optical ground-based telescopes. Photographic images enabled one to study the morphology of nebulae and galaxies, filters permitted the colors of stars and hence their surface temperatures to be estimated, and spectrographs recorded atomic spectral lines. After World War II, physicists developed radio astronomy, discovering relativistic particles from objects like neutron stars and black holes. NASA enabled astronomers to put instruments into earth orbit, gathering information from the ultraviolet, x-ray, infrared, and gamma-ray regions of the spectrum.

As the century opened, astrophysicists were applying classical physics to the orbits and internal structure of stars. The development of atomic physics enabled them to interpret stellar spectra in terms of their chemical composition, temperature, and pressure. Bethe (1939) demonstrated that the energy source of the sun and stars is fusion of hydrogen into helium. This discovery led astrophysicists to study how stars evolve when their nuclear fuel is exhausted and hence contributed to an understanding of supernova explosions and their role in creating the heavy elements. Study of the interstellar medium is allowing us to understand how stars form in our Galaxy, one of the billions in the expanding universe. Today the chemical elements created in supernova explosions are recycled into new generations of stars. A question for the future is how the galaxies formed in the first place.

II. STELLAR ENERGY AND EVOLUTION

A key development in astrophysics was Bethe's proposal that the carbon cycle of nuclear reactions powers the stars. H fuses with ^{12}C to produce ^{13}N, then ^{14}N, ^{15}O, and ^{15}N. The latter reacts with H to form ^{12}C again, plus ^{4}He. Thus each kilogram of H fuses to form slightly less than a kilogram of He, with the release of 6×10^{14} joules. Bethe was trying to find an energy source that would satisfy three conditions: (a) Eddington's finding (1926) that the central temperature of main-sequence stars is of the order of 10^7 K, (b) that the earth is Gigayears (Gy) old, and (c) that the sun and stars are mostly hydrogen. Bethe's cycle works on hydrogen at about 10^7 K, and the luminosity of the sun can be balanced for 10 Gy by burning only 10% of it.

The stage had been set by Hertzsprung (1911) and Russell (1914), who had found that, in a diagram in which the luminosity of a star is plotted against its surface temperature, most stars are found along a "main sequence" in which the hotter stars are brighter and the cooler are fainter. A sprinkling of stars are giants, which greatly outshine their main-sequence counterparts, or white dwarfs, which though hot, are faint. Eddington (1924) had found that the masses of main-sequence stars correlate well with their luminosities, as he had predicted theoretically, provided the central temperatures were all about the same. Bethe's proposal fitted that requirement, because the fact that only the Maxwell-Boltzmann tail of the nuclear reactants penetrates the Coulomb barrier makes the reaction rate extremely sensitive to temperature. But Bethe's discovery did not explain the giants or the white dwarfs.

Clues to this problem came with the application of photoelectric photometry to the study of clusters of stars like the Pleiades, which were apparently all formed at the same time. In such clusters there are no luminous—hence massive—main-sequence stars, while giants are common. In 1952 Sandage and Schwarzschild showed that main-sequence stars increase in luminosity as helium accumulates in the core, while hydrogen burns in a shell. The core gradually contracts, heating as it does so; in response, the envelope expands by large factors, explaining giant stars. Although more massive stars have more fuel, it is consumed far faster because luminosity increases steeply with mass, thus explaining how massive stars can become giants, while less massive ones are still on the main sequence.

The age of a cluster can be computed from the point at which stars leave the main sequence. Sandage found that ages of clusters range from a few million to a few billion years. In particular, globular star clusters—groups of 10^5 stars distributed in a compact region—all have the same age, about 10 Gy, suggesting that this is the age of the Galaxy. The article by Turner and Tyson in this volume explains why the age of globular clusters is a key datum in cosmology.

As more helium accumulates, the core of a star contracts and its temperature increases. When it reaches 10^8 K, ^{4}He burns to ^{12}C via the triple-α process discovered by Salpeter (1952); the core shrinks until the density is so high that every cell in phase space is occupied by two electrons. Further compression forces the electron momenta to increase according to the Pauli principle, and, from then on, the gas pressure is dominated by such momenta rather than by thermal motions, a condition called electron degeneracy. In response, the envelope expands to produce a giant. Then a ''helium flash'' removes the degeneracy of the core, decreasing the stellar luminosity, and the star falls onto the ''horizontal branch'' in the Hertzsprung-Russell diagram, composed of giant stars of various radii. Formation of a carbon core surrounded by a helium-burning shell is accompanied by an excursion to even higher luminosity, producing a supergiant star like Betelgeuse.

If the star has a mass less than eight solar masses, the central temperature remains below the 6×10^8 K necessary for carbon burning. The carbon is supported by degeneracy pressure, and instabilities of helium shell burning result in the ejection of the stellar envelope, explaining the origin of well-known objects called planetary nebulae. The remaining core, being very dense ($\sim10^9\,\mathrm{kg\,m^{-3}}$), is supported by the pressure of its degenerate electrons. Such a star cools off at constant radius as it loses energy, explaining white dwarfs.

Chandrashekhar (1957) found that the support of massive white dwarfs requires such high pressure that electron momenta must become relativistic, a condition known as relativistic degeneracy. ''Chandra,'' as he was called, found that for stars whose mass is nearly 1.5 times the mass of the sun (for a helium composition), the equation of state of relativistic degenerate gas requires that the equilibrium radius go to zero, with no solutions for larger mass. Though it was not realized at the time, existence of this limiting mass was pointing to black holes (see Sec. III).

Stars of mass greater than eight solar masses follow a different evolutionary path. Their cores do reach temperatures of 6×10^8 K at which carbon burns without becoming degenerate, so that contraction of the core to even higher temperatures can provide the thermal pressure required as nuclear fuel is exhausted. Shell burning then proceeds in an onion-skin fashion. As one proceeds inward from the surface, H, He, C, O, Ne, Mg, and Si are burning at successively higher temperatures, with a core of Fe forming when the temperature reaches about 2×10^9 K. When the mass of Fe in the core reaches a certain value, there is a crisis, because it is the most stable nucleus and therefore cannot release energy to balance the luminosity of the core. The core therefore turns to its store of gravitational energy and begins to contract. Slow contraction turns to dynamical collapse, and temperatures reach 10^{10} K. Heavier elements are progressively disintegrated into lighter ones, until only free nucleons remain, sucking energy from the pressure field in the process and accelerating the collapse. As the density approaches nuclear values ($10^{18}\,\mathrm{kg\,m^{-3}}$) inverse β decay ($p+e\rightarrow n+\mu$) neutronizes the material and releases about 10^{46} J of neutrinos, which are captured in the dense layers above, heating them to $\sim10^9$ K and reversing their inward collapse to outward expansion. Most of the star is ejected at 20 000 $\mathrm{km\,s^{-1}}$, causing a flash known to astronomers as a supernova of Type II. This scenario was confirmed in 1987 when Supernova 1987A exploded in the Large Magellanic Cloud, allowing 19 neutrinos to be detected by underground detectors in the U.S. and Japan. If the core is not too massive, neutrons have a degeneracy pressure sufficient to halt the collapse, and a neutron star is formed. Analogous to a white dwarf but far denser, about $10^{18}\,\mathrm{kg\,m^{-3}}$, it has a radius of about 10 km. The ''bounce'' of infalling material as it hits the neutron star may be a major factor in the ensuing explosion.

Ordinary stars are composed mostly of hydrogen and helium, but about 2% by mass is C, N, O, Mg, Si, and Fe, with smaller amounts of the other elements. The latter elements were formed in earlier generations of stars and ejected in supernova explosions. As the supernova shock wave propagates outward, it disintegrates the nuclei ahead of it, and as the material expands and cools again, nuclear reactions proceed, with the final products being determined by how long each parcel of material spends at what density and temperature. Numerical models agree well with observed abundances.

However, there is a serious problem with the above description of stellar evolution. In 1964 John Bahcall proposed that it be tested quantitatively by measuring on earth the neutrinos produced by hydrogen burning in the core of the sun, and that available models of the sun's interior be used to predict the neutrino flux. Raymond Davis took up the challenge and concluded (Bahcall *et al.*, 1994) that he had detected solar neutrinos, qualitatively confirming the theory, but at only 40% of the predicted flux, quantitatively contradicting it. Since then several other groups have confirmed his result. A new technique, helioseismology, in which small disturbances observed at the surface of the sun are interpreted as pressure waves propagating through its interior, allows one to determine the run of density and temperature in the interior of the sun. Increasingly accurate measurements indicate that Bahcall's current models and hence theoretical neutrino fluxes are accurate to about 1%, so the neutrino discrepancy remains.

The best solution to the solar neutrino problem may be that the properties of electron neutrinos differ from their values in the standard model of particle physics. Specifically, they may oscillate with tau neutrinos, and thus would have to have a rest mass. An upper limit of 20 eV on the neutrino mass deduced from the near-simultaneous arrival of the 19 neutrinos from Supernova 1987A is consistent with this hypothesis. Experiments are now under way to measure the energy spectrum of solar neutrinos and thereby check whether new physics beyond the standard model is needed.

III. COMPACT OBJECTS

Three types of compact stellar objects are recognized: white dwarfs, neutron stars, and black holes. White dwarfs are very common, and their theory is well understood. Models of neutron stars were presented by Oppenheimer and Volkoff in 1939. The gravitational binding energy in a neutron star is of the order of $0.1c^2$ per unit mass, so general relativity, rather than Newtonian physics, is required. As in the case of white dwarfs, neutron stars cannot exist for masses greater than a critical limiting value which depends upon the equation of state of bulk nuclear matter, currently estimated to be three solar masses.

If the evolution of a massive star produces a core greater than three solar masses, there is no way to prevent its collapse, presumably to the singular solution of general relativity found by Karl Schwarzschild in 1916, or that found for rotating stars by Kerr, in which mass is concentrated at a point. Events occurring inside spheres whose circumference is less than 2π times the "Schwarzschild radius," defined as $R_S = 2GM/c^2$ (=3 km for 1 solar mass), where G is Newton's constant, are forever impossible to view from outside R_S. In 1939 Oppenheimer and Snyder found a dynamical solution in which a collapsing object asymptotically approaches the Schwarschild solution. Such "black holes" are the inevitable consequence of stellar evolution and general relativity.

While optical astronomers despaired of observing an object as small as a neutron star, in 1968 radio astronomers Anthony Hewish, Jocelyn Bell, and their collaborators discovered a neutron star by accident, when they noticed a repetitive pulsed radio signal at the output of their 81-MHz array in Cambridge, England (Hewish *et al.*, 1968). The pulses arrive from pulsar PSR 1919 +21 with great regularity once every 1.337 sec. Hundreds of pulsars are now known.

Conservation of angular momentum can explain the regularity of the pulses if they are due to beams from a rotating object. The only type of star that can rotate once per second without breaking up is a neutron star. In 1975 Hulse and Taylor showed that PSR 1913+16 is in a binary system with two neutron stars of nearly the same mass, 1.4 solar masses. The slow decrease in orbital period they observed is exactly that predicted by the loss of orbital energy to gravitational radiation, providing the most stringent test yet of strong-field general relativity.

Giacconi *et al.* (1962) launched a rocket capable of detecting cosmic x rays above the atmosphere. They detected a diffuse background that has since been shown to be the superposition of thousands of discrete cosmic x-ray sources at cosmological distances. They also observed an individual source in the plane of the Milky Way, subsequently denoted Scorpius X-1. Later study by the *Uhuru* satellite revealed many galactic sources that emit rapid pulses of x rays, and the frequency of these pulses varies as expected for Doppler shifts in a binary system. X-ray binaries are systems in which a neutron star or black hole is accreting matter from a normal star and releasing gravitational energy up to 10^5 times the luminosity of the sun as x rays. Regular pulses are due to magnetized neutron stars in which accretion is concentrated at the magnetic poles. Even a tiny amount of angular momentum in the accreting gas prevents direct accretion, so the incoming material must form a Keplerian disk orbiting the compact object, supported by rotation in the plane of the disk and by much smaller thermal pressure normal to it. Solutions for thin disks give the rate at which angular momentum flows outward via turbulent viscosity, allowing material to accrete, and predict surface temperatures in the keV range, in agreement with observation.

In the 1960s, military satellites detected bursts of 100-keV gamma rays. Declassified in 1973 (Klebesadel, Strong, and Olson, 1973), gamma-ray bursts proved to be one of the most intriguing puzzles in astronomy, with theories proliferating. It is difficult to test them, because bursts last only seconds to minutes, usually do not repeat, and are hard to locate on the sky because of the lack of directionality in high-energy detectors. In 1997, the x-ray observatory *Beppo Sax* observed a flash of x rays coinciding in time with a gamma-ray burst from the source GRB 970228. The x-ray position was determined to within a minute of arc (IAU, 1997), allowing optical telescopes to detect a faint glow at that position. An absorption line originating in a galaxy in the same direction shows that the source is behind it, and hence at a cosmological distance (see Sec. V). Other x-ray afterglows have now confirmed that gamma-ray bursts are at cosmological distances, showing that the typical energy in a burst is 10^{45} joules. As this energy is 10% of the binding energy of a neutron star, a possible explanation is the collision of two neutron stars, inevitable when the neutron stars in a binary of the type discovered by Hulse and Taylor spiral together as a result of the loss of energy to gravitational radiation. Estimates of the frequency with which this happens agree with the frequency of gamma-ray bursts.

IV. GALAXIES

Our Galaxy, the Milky Way, is a thin disk of stars, gas, and dust, believed to be embedded in a much larger ball of dark matter. The nearby stars are arranged in a thin layer. Interstellar dust extinguishes the light of distant stars, and, until this was realized and allowed for, it appeared that the disk was centered on the sun and not much wider than it was thick.

In 1918 and 1919 Harlow Shapley used stars of known luminosities to estimate the distances to individual globular star clusters and found that they form an approximately spherical system whose center is 50 000 light years away in the constellation of Sagittarius (newer data yield a value closer to 30 000 light years). We now realize that the Milky Way is a disk about 30 000 light years in radius and 3000 light years thick, together with a thicker bulge of stars surrounding the center, which tapers off into a roughly spherical halo of stars. Many of the halo stars are located in globular star clusters described in Sec. II, of which there are several hundred. The sun revolves around the center once in 250 million years, and Kepler's third law applied to its orbit implies that mass inside it is about 10^{11} suns. We are prevented from seeing the galactic center by the enormous extinction of visible light by interstellar dust, but infrared radiation, which penetrates dust more easily, reveals that there is a very dense cluster of stars located right at the center of the Galaxy. To explain the very high observed velocities of the stars, there must be a compact object there with a mass of over 10^6 suns. This object is probably a massive black hole, a cousin of even more massive ones in active galactic nuclei (see below).

The morphology of the Galaxy reflects its origin and evolutionary history. Halo stars, in particular those in globular star clusters, are deficient in heavy elements. Since such elements are created in supernova explosions, this can be understood if halo stars formed early in the history of the Galaxy, when the number of supernovae was still small. Since globular star clusters all have about the same age, 10 Gy, it would fit the observations if the Galaxy formed by collapse of primordial material that long ago. Walter Baade gave the name Population II to halo stars, which are deficient in heavy elements and are old, and the name Population I to stars in the disk, which are younger and have normal abundances. The fact that Population I stars are confined to the disk of the Galaxy suggests that the interstellar gas from which they are still forming up to the present time was prevented from rapid star formation by its high angular momentum compared to that of the gas which formed the halo stars. Recent study suggests that the Galaxy is a barred spiral, in which the stellar orbits in the interior have coalesced into a bar like those seen in other galaxies. The spiral arms in the outer parts of the Galaxy are driven by the gravitational field of the bar, as explained theoretically in 1967 by C. C. Lin and Frank Shu.

In 1925 Edwin Hubble showed from the apparent brightness of stars of known luminosity that the distance of the nearby spiral galaxy M31 is about 1 million light years (now revised to 2 million), far larger than the 60 000-light-year diameter of our Galaxy, indicating that M31 is far outside it. Surveying galaxies to the limits of the 100-inch telescope on Mt. Wilson, Hubble concluded that the system of galaxies is at least 500 million light years in radius. Galaxies are distributed in groups of a few up to a few dozen galaxies, like the Local Group of which the Galaxy and M31 are a part, in clusters of 1000 galaxies or more, and in superclusters containing a dozen or more clusters. The modern view is that galaxies are clustered on all scales up to 300 million light years, while the distribution on even larger scales is nearly uniform.

Hubble discovered something else of monumental importance. Measuring Doppler shifts of galaxies at various distances (which he inferred from indicators like bright stars and exploding stars known as novae), he announced in 1929 that the radial velocities v of galaxies inferred from their Doppler shifts are always positive, indicating recession, and, further, that they are proportional to their distances r. This discovery caused a sensation. Hubble's law, $v=Hr$ (where H is called the Hubble constant), suggests a time in the past, $r/v=H^{-1}$, when the expansion apparently started. The expansion of the universe as a whole had been predicted on the basis of general relativity by Alexander Friedmann in 1922, but Hubble made no reference to that prediction in his 1929 paper. The implications of Friedmann's models for cosmology are described in the article by Turner and Tyson in this volume. Here we note that Hubble's law enables one to estimate the distance of any galaxy for which the Doppler shift is known, once the Hubble constant H is determined from galaxies of known distance.

Back to the origin of the elements. George Gamow proposed in 1946 that all of the elements were created in the first few minutes of the cosmological expansion, when, he calculated, the energy density was dominated by radiation rather than by matter. Under these conditions, Friedmann's equations show that the temperature T is related to the age t of the universe by $T \simeq 1\ \mathrm{MeV}/\sqrt{t}$ if t is in seconds. With Alpher and Bethe, Gamow showed in 1948 that the protons and free neutrons at such temperatures would react to form helium, but because of the lack of a stable nucleus of mass 5, nuclear reactions would stop there, contradicting his hypothesis that all of the elements are created in the first few minutes. As we have seen above, conditions in supernovae produce the elements heavier than helium, and in 1957 Burbidge, Burbidge, Fowler, and Hoyle were able to assign the origin of all the heavier elements to one of several processes occurring in evolved stars, such as the triple α reactions described earlier, the slow addition of free neutrons, and the rapid addition of neutrons that occurs in supernova explosions. Fred Hoyle recognized that the helium must be made in Gamow's "Big Bang," as Hoyle referred to it, and with Roger Tayler, he made an early calculation of the expected helium abundance based on modern nuclear data. It is now believed that H and He were formed in the big bang, and that all the other elements are formed in supernovae.

Penzias and Wilson (1965) discovered an isotropic microwave background radiation at 7.3-cm wavelength, having a brightness temperature 3.5 ± 1 K, since then referred to as the CMB, for cosmic microwave background (see the article by Wilkinson in this volume) and interpreted this as radiation from the big bang. The discovery of the CMB solved a puzzle I had known about for years. Optical absorption by interstellar CN molecules in the upper rotational level is observed in the spectra of distant stars, so that level is somehow excited. In an unpublished note I had shown that the excitation must be due to radiation at a wavelength of 2.6 mm having a brightness temperature of about 3 K. I was thus able, in 1966 and with John Hitchcock, to use his recent CN measurements to show that the spectrum of the CMB is that of a blackbody over the wavelength interval from 7.3 cm to 2.6 mm, a factor of 30.

One discovery in extragalactic astronomy was completely unexpected—supermassive black holes. The story goes back to Seyfert (1943), who noticed that about 1% of spiral galaxies are anomalously bright. He found that the emission is highly concentrated at the nucleus of the galaxy, rather than spread over its surface, and that the optical spectrum consists of emission lines of hot gas. Moreover, these lines are so wide that if they are due to the Doppler effect, atoms must be moving at an unprecedented several thousand $\mathrm{km\,s^{-1}}$.

Later, radio astronomers began to localize radio sources using Michelson interferometry, enabling a number of sources to be identified optically. It was a great surprise when Cygnus A, the second brightest radio source, was identified by Rudolph Minkowski with a galaxy 500 million light years from the earth. Although 10^{11} times more distant than the sun, it appears brighter at radio wavelengths. Cygnus A opened an era of extragalactic radio astronomy in which each new survey revealed larger numbers of ever-fainter radio galaxies distributed isotropically and therefore most likely at cosmological distances. Their spectra and, later, their polarization properties revealed that the emission is synchrotron radiation, that is, high harmonics of cyclotron radiation by relativistic electrons trapped in magnetic fields. Geoffrey Burbidge showed that to explain the observations there must be a minimum energy in particles and fields. For Cygnus A and other powerful extragalactic sources, this minimum energy is 10^{53} joules, equivalent to the rest mass of 10^6 suns. Nuclear energy cannot be released fast enough to account for the powerful radio galaxies.

Improved interferometers revealed that a radio galaxy typically has two synchrotron clouds disposed on either side, with a point source at the nucleus of the galaxy and jets leading to the lobes, demonstrating that the galactic nucleus is the energy source. Optical astronomers discovered that the spectra of the nuclei of radio galaxies are similar to those of Seyfert galaxies, while radio astronomers studying Seyfert galaxies discovered that they also emit radio waves.

Schmidt (1963) obtained an optical spectrum of a compact radio source, 3C273, and found the Balmer spectrum of hydrogen in emission, shifted to longer wavelengths by 15%, corresponding to a recession velocity of 45 000 $\mathrm{km\,s^{-1}}$. Many other such objects were found and given the name ''quasistellar radio source,'' or quasar. Their high redshifts mean that quasars are at cosmological distances, and they appear to be compact because of their great distances. The nearer ones have now been resolved by the Hubble Space Telescope, showing that this is correct.

Today we recognize that Seyfert galaxies, radio galaxies, quasars, and QSO's (luminous pointlike extragalactic objects that have little radio emission) belong to a single class of object called active galactic nuclei, which are energized by a powerful engine in the nucleus. The luminosity, radio-to-optical ratio, and presence or absence of a jet are determined by local circumstances. X-ray and even γ-ray emissions have now been observed from many such objects, and their characteristics can be understood in the context of such a model.

The key question is the nature of the central engine. The fact that nuclear energy does not suffice leads to the suggestion of gravitational energy, released as material accretes onto a compact object, as in x-ray binary stars. Because the total energy requires masses of millions of suns, which vastly exceeds the mass of a neutron star, only a supermassive black hole will do.

Rarely seen in Seyfert galaxies, but common in quasars, jets are remarkably well collimated, maintaining their structure for hundreds of thousands of light years. As the polarization is aligned with the jet, coherent magnetic structures must be involved. In the model of Blandford and Znajec, a spinning black hole briefly interacts with the magnetic field of accreting material, setting up a vortex that leads to jet formation. Only such a mechanism seems capable of accelerating those jets for which the Lorentz factor must be 10 to 100.

How are supermassive black holes formed? The ''best-buy model,'' favored by Martin Rees, is that collisions among stars in the dense nucleus of a galaxy produce gas that spirals in by turbulent viscosity to feed a black hole through an accretion disk.

V. THE INTERSTELLAR MEDIUM AND STAR FORMATION

In the 1940s, Lyman Spitzer, Jr., recognized that the youth of Population I star clusters demands that stars must be forming ''now,'' and that the only available mass reservoir is the interstellar gas recognized at that time from optical interstellar absorption lines in the spectra of distant stars. Strömgren (1939) had shown that the emission nebulae observed near hot giant stars can be explained by the photoionization of nearby clouds of hydrogen. Photons above the 13.6-eV ionization limit of hydrogen ionize hydrogen from HI to HII out to a distance such that the number of recombinations balances the number of ionizing photons. Photoionization heating balances emission-line cooling at a kinetic temperature of about 10^4 K, as confirmed by the strength of emission lines in HII regions.

The absence of ionizing photons outside of HII regions leaves hydrogen in the atomic state (HI), and Spitzer and Savedoff (1950) calculated that the kinetic temperature of HI regions should be of the order of 100 K. However, measurements of temperature and density were not possible at that time, because the absorption lines of HI in its ground state are in the far ultraviolet. I showed (Field, 1965) that the thermal equilibrium of high-density HI is stable, but that low-density gas is unstable to the formation of dense clouds surrounded by hot gas. Such multiphase gases are observed in a variety of astrophysical contexts.

In 1945 van de Hulst calculated that the 21-cm line in the ground state of interstellar HI, due to the $F=3/2 \rightarrow 1/2$ hyperfine transition, would be observable. In 1951 Ewen and Purcell detected 21-cm emission from the Milky Way. Soon confirmed by groups in Holland and Australia, the 21-cm line provided an important tool for measuring physical conditions in interstellar space as well as the dynamics of the Galaxy. Spitzer's prediction that $T \sim 100$ K was verified. The emission at various angular distances from the galactic center reveals a roughly circular distribution of HI, forming spiral arms that correlate with the distribution of Pop I stars, consistent with the formation of such stars from interstellar gas. The total mass of HI, 2×10^9 solar masses, is about 2% of the gravitational mass inside the sun's orbit.

The 21-cm line has been used to observe HI in other spiral galaxies. Typically, for distances comparable to the sun's orbit, the results are not unlike the Galaxy. But whereas our position in the Galaxy makes it difficult to estimate the distance of HI outside the Sun's orbit, this is not true of external galaxies. As stellar emission is observed to decrease sharply away from the center of a spiral galaxy, most of the stellar mass is concentrated within 30 000 light years, so that at large distances R there should be Keplerian rotation, with $V\propto R^{-1/2}$. However, it is observed that $V(R)\sim$const out to the largest distances measured. To balance the larger implied centrifugal force, gravitation must be stronger, implying the presence of large amounts of dark matter, either baryonic (faint stars, black holes, etc.) or perhaps nonbaryonic matter created in the big bang (see the article by Sadoulet in this volume). The baryon-to-photon ratio implied by the deuterium abundance is so low that the former is not very credible, so most cosmologists lean toward the latter, with the accompanying implications for the standard model of particle physics described in the article by Turner and Tyson in this volume.

In 1937 Zwicky found that the masses of individual galaxies, deduced by application of the virial theorem to clusters of galaxies, are much greater than those inferred from studies of the inner, stellar, parts of galaxies. He proposed that galaxies had unseen matter in their outer parts, and as stated above, this has now been verified for spiral galaxies from their rotation curves. More recent studies of the distribution of hot x-ray-emitting gas in elliptical galaxies confirms the need for dark matter there too.

In Spitzer's day astronomers had noted the presence of dust clouds in the Milky Way that extinguish the light of stars behind them. Although densities must be thousands of times greater than the interstellar average, 21-cm observations detected no HI, and Salpeter proposed that in such clouds hydrogen is converted to H_2 molecules by reactions on the surfaces of interstellar dust particles. H_2 was found in a rocket ultraviolet absorption spectrum by George Carruthers in 1970, and NASA's *Copernicus* ultraviolet satellite observed H_2 in all regions where the extinction is high enough to shield it from photodissociating photons. The amount of H_2 in the Galaxy is about equal to that of HI.

As the youngest stars are found in or near dark clouds, these clouds, which must be molecular, are the places where stars are born. To assess conditions within them, a type of emission is needed that can penetrate the dust. Emission by the OH radical at 1665 MHz, to which dark clouds are transparent, was found in 1965 by Weinreb, Barrett, Weeks, and Henry. Since then, over 100 different molecular species have been found in the microwave and mm-wave regions, the latest with 11 carbon atoms. Carbon monoxide is widespread and has been detected in distant galaxies. It has been found that individual "cores" of molecular clouds, having masses of the order of one solar mass, are contracting at several $10^2\,\mathrm{m\,s^{-1}}$, presumably to form new stars like those observed in their vicinity, confirming that stars are forming today in molecular clouds.

Throughout the interstellar medium there are enough free electrons that the medium can support electric currents and hence magnetic fields. That such fields are present was inferred in 1949 by Hiltner and by Hall from the alignment of interstellar dust particles discovered to polarize the radiation of distant stars. The necessity of galactic magnetic fields was recognized by physicists, who demonstrated that there was a high degree of isotropy in the arrival directions of cosmic rays. This isotropy can be explained by gyration around a field. In 1977–1978 it was shown independently by several groups that shock waves in the magnetized interstellar medium can accelerate charged particles to cosmic-ray energies. Such shocks are observed around old supernovae, and the energetics work out.

Hannes Alfvén demonstrated that the motion of a gas with high electrical conductivity like the interstellar medium drags the magnetic field along with it, conserving magnetic flux as it does so. This effect is important for the contraction of molecular cloud cores because it increases the magnetic stress, resisting further contraction. Star formation is delayed while the neutral gas molecules slowly drift through the ions stuck to the field. When enough molecules have accumulated, self-gravitation takes over, and the core collapses to form one or more stars.

It is now appreciated that the Galaxy is a dynamic place, with supernova explosions heating and accelerating surrounding gas and providing fresh heavy elements to it. Subsequently some of this gas collapses to form new stars, some of which explode as new supernovae. In this way, a spiral galaxy like our own, born in the collapse of dark matter from the expanding universe, slowly converts its gas to stars, a process that will cease only when all the gas has collapsed to form stars whose masses are too small for them to explode.

VI. A PERSONAL PERSPECTIVE

My career in astrophysics started when I was about 12 years old at the William H. Hall Free Library in Edgewood, Rhode Island. It housed, among other things, a small group of books by Sir James Jeans and Sir Arthur Eddington, theoretical astrophysicists in Cambridge, England.

Eddington, who was the first to show from first principles why the stars shine with the power they do, wrote lucidly for the public about stars, galaxies, and the universe. I was hooked; when asked about my future career for the high school yearbook, I unhesitatingly replied, "theoretical astrophysicist." Why theory, not observation? Jeans and Eddington certainly influenced me this way; but there was also the fact that I never seemed to get a big enough explosion in my basement chemistry lab, while mathematics is precise, powerful, and predictable. At MIT I majored in physics and mathematics. For my bachelor's thesis I did an experiment under Hans

Mueller on the alignment of small particles in a fluid by an electric field to simulate the then recently discovered polarization of starlight by interstellar dust. As I recall, the data were nearly useless, but the theoretical analysis was not bad.

I had read George Gamow's *Creation of the Universe*, so when I found myself working in a Department of Defense lab in Washington during the Korean War, in 1951–1952, I attended night courses Gamow gave at George Washington University. I admired Gamow's quick mind and fun-loving personality. He speculated in class about the structure of DNA, and explained how his theory of nucleosynthesis in the big bang accounted for the chemical elements.

To decide on a graduate school, I read articles in the Astrophysical Journal at the Library of Congress, and found those by Lyman Spitzer, Jr., at Princeton the most interesting. I applied and got in, in part, I learned later, because Gamow had sent a postcard saying "Field is OK."

At that time the Princeton Observatory was housed in a Victorian building attached to the Director's home. Departmental teas around a big table in the room which joined the house to the Observatory were memorable for the sparkling conversations between Lyman Spitzer and Martin Schwarzschild, two of the world's leading astrophysicists. I recall their discussing the recent discovery by Nancy Roman that the abundance of heavy elements in stars, as judged by the intensity of absorption lines in their spectra, is correlated with their space velocities relative to the sun, with the low-abundance stars moving faster—an intriguing puzzle. Spitzer's and Schwarzschild's discussion that day led to a paper in which they showed that recently discovered massive clouds of interstellar gas perturb the orbits of stars in the Galaxy over time, so that the oldest stars would have the largest spread in velocities, as observed. I had witnessed the solution of a problem in theoretical astrophysics, in which theoretical dynamics joined nuclear physics and stellar spectroscopy to explain an observed fact. Great stuff!

Radio astronomy was then a relatively new field, and I was excited when Ewen and Purcell discovered 21-cm-line emission from interstellar atomic hydrogen in the Galaxy. I suggested searching for 21-cm absorption against a suitable background radio source and began to think about applications to cosmology. I had taken a course in relativity with John Wheeler and had listened to lectures by Fred Hoyle, a visitor to the Observatory, expounding his steady-state theory, which made a firm prediction for the mean density of the universe. As the stars in galaxies contribute far less than the predicted amount, I decided to search for hydrogen residing between the galaxies in intergalactic space.

So as a postdoc at Harvard I searched for an absorption "trough" between 21 cm and $21(1+z)$ cm, the wavelength of the line shifted to the velocity $v=cz$ of the source, where intergalactic hydrogen should absorb according to Robertson-Walker cosmology. I measured the brightness of the Cygnus A radio source, a radio galaxy with a redshift $z=0.057$ and observed no effect, and so could only put an upper limit on intergalactic hydrogen. Much later, when quasars were discovered with redshifts about 2, the Lyman-α resonance line at 122 nm of intergalactic HI near the quasar was redshifted to 365 nm, where it can be observed from the ground. Soon a whole "forest" of intergalactic Ly-α lines were discovered, with many implications for cosmology. Intergalactic HI is there after all, but it is clumped into clouds to which my experiment was insensitive. In any event, the amount of HI is not sufficient to contribute significantly to the mass of the universe.

One of the inputs I needed to calculate the excitation of the 21-cm line was the background radiation temperature T_R at 21-cm wavelength. Doc Ewen told me that an absolute measurement of T_R was not feasible at that time. I discussed the same issue with Arno Penzias much later, but neither of us, as I recall it, made any connection with Alpher and Herman's (1948) prediction that there should be a background radiation from the big bang with a temperature of about 5 K. Penzias and Robert Wilson later discovered the 3-degree microwave background, which had such an impact on cosmology.

I then returned to teach at Princeton and worked on problems of the interstellar medium, cosmology, and planetary science. Over the years I have written papers on the Moon, Mercury, Jupiter, and comets, the latter stimulated by the collision of the Shoemaker-Levy cometary fragments with Jupiter in 1993. I found that the literature on hypersonic reentry contains conceptual errors and was able to interpret modern numerical simulations in terms of the growth and saturation of Kelvin-Helmholtz and Rayleigh-Taylor instabilities in the melted fragment material. My paper with Andrea Ferrara on the subject, with its predictions of post impact phenomena, was accepted on 15 July, 1994, the day before the impacts began. The planets present a fascinating variety of solvable physical problems, which provide a welcome respite from the relatively intractable problems presented by the interstellar medium.

VII. THE FUTURE

World astronomy is now building new telescopes at an unprecedented rate. Following the success of the two 10-m Keck telescopes on Mauna Kea, a dozen large (6-to-10-m) telescopes are under construction. Planning is under way for a Next Generation Space Telescope, to be launched in 2007, and the Hubble Space Telescope will continue operations until 2010. In 1999, NASA will launch the Advanced X-Ray Astrophysics Facility, capable of sub-arcsecond imaging in the 1-to-10-keV band. Two satellites will measure the cosmic microwave background with sufficient precision to determine most cosmological parameters. LIGO, a ground-based laser interferometer, will search for gravitational waves emitted by collisions of black holes and neutron stars. Neutrino experiments will test whether neutrino oscillations are responsible for the famous deficit of solar neutrinos. Additional observing facilities at millimeter, submillimeter, and infrared wavelengths will come on-line.

It is astonishing that citizens of the world are willing to pay for these instruments, which have little prospect of improving their material lives. Something else is at work here, probably widespread curiosity about the natural world in which we find ourselves. While supernova explosions are far away, and galaxies forming in the early universe remoter still, taxi drivers and bartenders pause when they hear that until one of those supernova explosions occurred, most of the material on earth did not exist. Astrophysicists are trying to figure out how it all happened, and to do so with the best physics they can command.

REFERENCES

Alpher, R. A., H. Bethe, and G. Gamow, 1948, Phys. Rev. **73**, 803.

Alpher, R. A. and R. C. Herman, 1948, Nature (London) **162**, 774.

Bahcall, J. N., 1964, Phys. Rev. Lett. **12**, 300.

Bahcall, J. N., R. Davis, P. Parker, A. Smirnow, and R. Ulrich, 1994, *Solar Neutrinos: The First Thirty Years* (Addison-Wesley, Reading, MA).

Bethe, H. A., 1939, Phys. Rev. **55**, 434.

Burbidge, E. M., G. R. Burbidge, W. A. Fowler, and F. Hoyle, 1957, Rev. Mod. Phys. **29**, 547.

Chandrasekhar, S., 1957, *An Introduction to the Study of Stellar Structure* (Dover, New York).

Eddington, A. S., 1924, Mon. Not. R. Astron. Soc. **84**, 308.

Eddington, A. S., 1926, *The Internal Constitution of the Stars* (Cambridge University, Cambridge).

Ewen, H. I., and E. M. Purcell, 1951, Nature (London) **168**, 356.

Field, G. B., 1965, Astrophys. J. **142**, 531.

Giacconi, R., H. Gursky, F. R. Paolini, and B. B. Rossi, 1962, Phys. Rev. Lett. **9**, 442.

Hertzsprung, E., 1911, Publ. Astrophys. Obs. Potsdam **22**, No. 63.

Hewish, A., S. J. Bell, J. D. H. Pilkington, P. F. Scott, and R. A. Collins, 1968, Nature (London) **217**, 709.

Hubble, E. P., 1929, Proc. Natl. Acad. Sci. USA **15**, 168.

Hulse, R. A., and J. H. Taylor, 1975, Astrophys. J. **195**, L51.

IAU, 1997, International Astronomical Union Circular No. 6576, March 6, 1997.

Klebesadel, R., I. B. Strong, and R. A. Olson, 1973, Astrophys. J., Lett. Ed. **182**, L85.

Oppenheimer, J. R., and G. M. Volkoff, 1939, Phys. Rev. **55**, 374.

Oppenheimer, J. R., and H. Snyder, 1939, Phys. Rev. **56**, 455.

Penzias, A. A., and R. W. Wilson, 1965, Astrophys. J. **142**, 419.

Russell, H. N., 1914, Popular Astron. **22**, 275.

Salpeter, E. E., 1952, Astrophys. J. **115**, 326.

Sandage, A. R., and M. Schwarzschild, 1952, Astrophys. J. **116**, 463.

Schmidt, M., 1963, Nature (London) **197**, 1040.

Schwarzschild, K., 1916, Sitzungsber. K. Preuss. Akad. Wiss. Berlin **1**, 189.

Seyfert, C. K., 1943, Astrophys. J. **97**, 28.

Shapley, H., 1918, Astrophys. J. **48**, 154; 1919, **49**, 311.

Spitzer, Jr., L., and M. P. Savedoff, 1950, Astrophys. J. **111**, 593.

Strömgren, B., 1939, Astrophys. J. **89**, 526.

van de Hulst, H. C., 1945, Ned. Tijdschr. Natuurkd. **11**, 210.

Zwicky, F., 1937, Astrophys. J. **86**, 217.