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Cosmic Electromagnetic Radiation

The sky shine covers an enormous spectrum of frequencies, revealing a cosmic picture in some detail.

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Visible light, covering less than one octave of frequency, was once the only known part of the electromagnetic spectrum. Defined as the band of frequencies to which the human eye is sensitive, visible light also makes up most of the solar emission spectrum. And whereas the earth's atmosphere blocks almost all other radiation, visible light penetrates thick layers of air, with little absorption. The chance coincidence between the color of sunlight and the optical properties of air was, of course, essential for the development of life on the earth. The evolution of the eye was less of an accident; redder or bluer sunlight would have led to the evolution of appropriate organs of somewhat different structure.

The narrow band of visible light carries a wealth of information about worlds far from the earth. Man's ability to see the planets with good angular resolution, and so to chart their positions with great precision, made possible the development of mechanics as an exact science. With the help of the telescope and the spectrograph, astronomers have analyzed the properties of distant stars and have constructed a set of yardsticks which extend our measures of length and time to the limits of visibility. Thus, the modern sciences of astrophysics and cosmology have made their appearance. The optical study of the sun itself has been elaborate and fruitful.

But the visible band is a very small part of the total electromagnetic spectrum that science has recently learned to explore. Stretching from radio waves to gamma rays, the spectrum of extraterrestrial signals spans 100 octaves of frequency. The process of gathering and interpreting information from the invisible bands is still in its infancy, having begun only a few decades ago. But it is already clear that our picture of the world is taking form more rapidly than ever before. I attempt, in this article, to suggest some of the recent additions to this picture.

It is useful to begin with some simple matters that are common to most of the investigations. All forms of electromagnetic radiation propagate through empty space at the same speed: $c = 3 \times 10^8$ m/sec. Any beam of radiation in a small spectral interval can be regarded as a wave of frequency ν, or as a stream of photons of energy $E = h\nu$. When ν is measured in cycles per second and E in electron volts (ev), the constant h has a numerical value of about 4×10^{-15}. Thus, visible light, which has frequencies around 10^{15} cy/sec, consists of photons with energies of a few electron volts. The highest photon energies so far revealed in the study of cosmic rays are in the neighborhood of 10^{20} ev.

The energy fluxes reaching us from celestial sources also span many orders of magnitude. Solar radiation arrives at the top of the earth's atmosphere at the rate of 8.4×10^{17} ev cm^{-2} sec^{-1}, or about 2×10^{17} photons per square centimeter per second. Since the sun is 1.5×10^{13} cm away, it must have a luminosity of 2.4×10^{45} ev/sec. How far away is a sunlike star which is barely visible? The limit of sensitivity of the naked eye corresponds to a flux of about 10^4 ev cm^{-2} sec^{-1}. Thus, from the law of inverse squares, we calculate that we can see sunlike stars out to 10^7 times the solar distance—that is, to distances of about 100 light-years (1 light-year $\cong 10^{18}$ cm). The viewing limit for the 200-inch (508-cm) telescope on Mt. Palomar corresponds to fluxes a million times weaker. Thus the telescope can photograph single stars out to about 10^5 light-years. When it views entire galaxies, with luminosities about 10^{10} times the luminosity of a single star, this telescope can record objects that are billions of light-years away.

Next in importance after sensitivity is the angular resolution of a detector. The eye can resolve two point sources separated by as little as 10 seconds of arc; theoretically the 200-inch telescope can resolve two point sources separated by a distance about 1000 times smaller. Instead of expressing the resolution as an angular limit, we prefer to speak of the solid angle of the corresponding circular cone. A cone of half-angle θ has solid angle $2\pi (1 - \cos \theta)$ steradians. Thus the limit of resolution for the 200-inch telescope is a cone of solid angle 10^{-14} steradian.

The resolution of a detector determines the precision with which an observer can locate an object in the sky. It also bears significantly on the problem of separating signal from background. Thus, when we look at

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stars in the night sky, we see them against a general background glow. The strength of the general glow is such that, if the angular resolution of the eye were a few degrees instead of a few seconds of arc, very few stars would be seen as single sources. Now, it is a stubborn fact that present detection techniques for invisible regions of the spectrum have poor resolution. The best interferometers in radio astronomy have limits of about 10^{-7} steradian, a resolution poorer by an order of magnitude than the limit for the eye. Detectors in the x-ray and gamma-ray regions have resolutions even worse than this, with limits of the order of 0.1 steradian. With these detectors we are unable to pinpoint the positions of small sources, and their signals may easily be masked by an extended sky glow. But the spectrum of the general glow is itself an object of study, for which existing detectors are of considerable value.

I turn now to a brief description of the physical processes which give rise to cosmic electromagnetic radiation. Thermonuclear reactions in the central regions of stars are responsible for the surface glow that we see as starlight. With one great exception, no radiation from the deep interior of a star is accessible to us. The exception is the neutrino flux, which escapes easily, carrying a large fraction of the total power output and traveling at the speed of light. Neutrinos are not a form of electromagnetic radiation, and they interact so weakly that they are enormously difficult to detect. An effort toward a beginning of neutrino astronomy is currently being made in several laboratories. Despite its importance, I regard it as outside the scope of this article.

Atomic transitions in the photospheres of stars give rise to electromagnetic radiation in and around the visible band of the spectrum. The local energy density of starlight is about 1 ev/cm^3. The density in the galactic halo is about one-third as large; the density in metagalactic space is about 10^{-3} ev/cm^3.

Synchrotron Radiation

There is another source of radiation, which contributes not only to the visible spectrum of certain unusual celestial objects but also to fluxes commonly observed in other regions of the spectrum. When an electron of speed v and total energy E circulates in a magnetic field B, it emits synchrotron radiation (*1*) with a spectrum in which the peak flux has the characteristic frequency

$$\bar{\nu}_s = 1.26 \times 10^{-6}\ \gamma^2\ B_p\ \text{Mcy/sec} \quad (1)$$

where $\gamma = E/mc^2$ and $B_p = B \sin \theta$, θ being the angle between v and B. The unit of magnetic field in the formula is the microgauss; a field strength measurable in microgauss is typical of interstellar space in our galaxy. An electron of energy 10^3 Mev has $\gamma = 2 \times 10^3$, radiates at the peak frequency 5 Mcy/sec when $B_p = 1$, and thus contributes to the radio spectrum. Synchrotron radio emission occurs within our galaxy, giving immediate evidence of the presence of fast electrons and large-scale magnetic fields. Observation of this signal led to the discovery (*2*) of the galactic halo.

Synchrotron radiation extends into the visible spectrum when electron energies and magnetic fields are sufficiently large. The radiation from the Crab nebula, a supernova remnant in our galaxy, appears to be a clear example of an extended synchrotron spectrum. The luminosity of this object at 100 Mcy/sec is about 10^{36} ev/cy; thus it is one of the brightest radio sources in the sky. The radio spectrum is fairly flat over five octaves and thus cannot be of thermal origin. At the same time, the Crab has a luminosity of 3×10^{33} ev/cy in the visible region; the visible spectrum, too, appears to be of nonthermal origin. The light shows a high degree of polarization, a property of synchrotron radiation. Taken together, these observations suggest that the glowing regions of the Crab contain magnetic fields of the order of 10^4 microgauss and electrons with energies up to 10^{11} ev. And this suggests, in turn, that whatever mechanism is accelerating electrons can also operate on nuclei. Thus we are led to suspect that supernovae are sources of cosmic rays (*3*).

The theory of synchrotron radiation tells us that the power radiated by an electron is

$$P_s(\gamma) = 10^{-15}\ \gamma^2 B_p^2\ \text{ev/sec} \quad (2)$$

with γ and B_p defined as before. We can predict the spectrum of radiation from a given source if we know the distribution of magnetic fields and electrons throughout the source. Conversely, measurements of the radiation reveal properties of the electron and field distributions.

Let us consider the galactic radiation from these alternative points of view. We know that the interstellar regions of the galactic disk contain moving gas clouds that produce an average density for these regions of about 1 atom per cubic centimeter. The matter density in the galactic halo is lower by an order of magnitude. The gas is highly ionized and its motion produces a general magnetic field whose strength can be estimated in several ways. From the fact that the energy density of the gas must be at least as great as the energy density of trapped cosmic radiation, we know that the field strength in the galactic disk must be at least 5 microgauss. From the Zeeman splitting of the 21-centimeter absorption line of neutral hydrogen, we know that the field cannot be much greater than 5 microgauss. This value therefore represents a good estimate of the general field.

Galactic Electron Sources

If the flux of cosmic rays observed at the earth is typical of the whole galaxy, cosmic rays generate π-mesons by interaction with interstellar matter at a rate that we can calculate. These mesons decay into muons, and thence into positrons and electrons, forming what we call a *secondary* electronic component of cosmic radiation. Energy spectra for this component, calculated by Hayakawa (*4*), appear in Fig. 1. We see that the positrons are predominant, that the peaks occur at about 50 Mev, and that the spectra, at high energy, fall off as the 5/2 power. If we take for the flux of galactic cosmic rays the value observed at the earth, we calculate the rate at which these secondary components are produced to be of the order of 10^{41} per second for the entire galactic disk. The energy radiated by positrons and electrons with energies above 10^9 ev is 10^{40} ev/sec. But this is less by one or two orders of magnitude than the total energy associated with the observed radio spectrum. Furthermore, the observed spectrum is somewhat flatter than one would expect from the energy distributions of Fig. 1. Thus we suspect that the secondary electronic component cannot, by itself, supply the energy required for galactic synchrotron radiation.

What other sources of electrons can be found? Recalling the discussion of the radiation from the Crab, we might suppose that there are special regions in the galaxy where electrons are accelerated to high energies. We call such electrons a *primary* electronic component. If the Crab is a typical supernova remnant, and if we know the frequency at which supernovae occur in the galaxy, then we can estimate the rate at which such sources supply the galaxy with primary electrons.

The records of Chinese astronomers indicate that supernova explosions were seen in the years A.D. 185, 369, 1006, and 1054. Tycho Brahe observed a supernova in A.D. 1572, and Johannes Kepler saw one in 1604. In addition, there is an unconfirmed report, by Arabian astronomers, of a supernova in the year A.D. 827. Thus, supernovae have been seen at the rate of about one per 200 years. The identification of their remnants with currently observable objects has been satisfactory. Most obvious is the Crab nebula, associated with the event of 1054. Strongest of all radio sources in the sky is Cassiopeia A, whose position agrees well with the event of the year 369. Positions of radio sources also show good agreement with observations for the years 185, 1572, and 1604. The Arabian event may in fact have been a comet, but it agrees with the position of a recently discovered x-ray source. Telescopic studies of other galaxies have revealed more than 50 supernovae events in 75 years; in each of three galaxies the rate has been about one per 20 years.

It is likely that none of the supernovae observed in our galaxy is farther away than 10^4 light-years. It seems probable that supernovae are occurring at a uniform rate throughout the galaxy; if they are, we can guess that the total rate of about one per 10^8 seconds is typical of any galaxy. Now the number of electrons produced in each explosion is of the order of 10^{50}. Thus, the average rate for the galaxy is of the order of 10^{42} primary electrons per second, ten times the estimate given above for the rate of production of secondary electrons. If their energies are sufficiently high, primary electrons can contribute to the galactic synchrotron radiation in a significant way.

Cosmic Ray Electrons

A crucial experiment, bearing on our understanding of galactic radiation, is the direct measurement of the electronic component of cosmic rays. In the experiment, we look at a local sample of the galactic positron and electron fluxes; the experimental result is a strong test of the production hypotheses that I have been describing. Both the strength of the electronic component and the shape of its energy spectrum are important things to know. And the ratio e^+/e^- (number of positrons to number of electrons) helps us to assess the relative importance of primary and secondary processes to the total electronic component. Since cosmic rays and interstellar hydrogen are known to pervade the galaxy, proton-proton collisions leading to the production of secondary electrons are certain to occur. If this process predominates, the charge ratio should be $e^+/e^- \cong 2$ at energies near 100 Mev, and should approach unity at higher energies. But if primary acceleration is the predominant process, there should be few positrons in the cosmic ray flux.

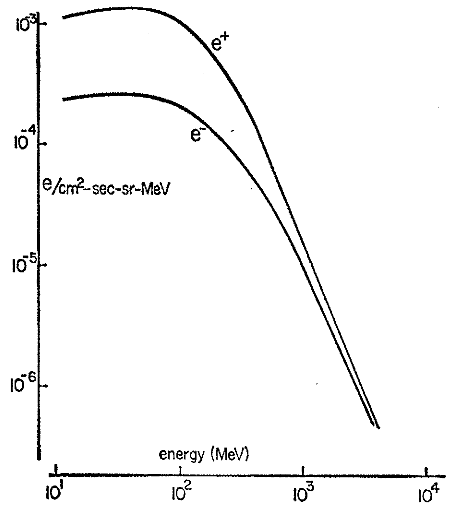

Fig. 1. Electron and positron spectra predicted from the decay of mesons produced by collisions of cosmic ray protons with interstellar hydrogen.

It has been known (*5*) for more than a decade that the electronic component cannot be greater than about 1 percent of the total cosmic ray beam. Two independent experiments (*6*), published simultaneously in 1961, gave the first direct evidence that an electronic component exists in the galaxy. The flux in the energy interval from 25 to 100 Mev is approximately 0.03 electron per square centimeter per second per steradian. A more recent experiment (*7*), in which five spark chambers and a magnetic deflector were taken to the top of the atmosphere by a balloon, has yielded valuable data on the e^+/e^- ratio. For example, the ratio measured at energies around 500 Mev is 0.19 ± 0.06; there are five times as many electrons as positrons. But the prediction for secondary processes alone (*4*) is $e^+/e^- = 1.5$. It appears, therefore, that a major part of the electronic flux is primary in character.

Although the e^+/e^- experiment has not yet given energy spectra of the two components, from the energy dependence of the ratio we can arrive at the shapes of these spectra indirectly. Let us assume that the flux is of galactic origin and that all positrons are of secondary origin, their spectrum being of the form shown in Fig. 1. Then the electron flux can be calculated from the ratio. We find that the resulting spectrum falls less steeply with increase in energy than the spectrum of secondaries alone does. It behaves, in fact, more nearly like the spectrum one would expect from the frequency dependence of the observed synchrotron radiation (*8*).

In the early days of cosmic ray physics, when evidence that protons are the primary particles was mounting, physicists sought explanations for the relative scarcity of electrons. Since it seemed reasonable to suppose that the cosmic ray sources produce electrons as copiously as protons, the subsequent disappearance of the electrons would have to be a result of energy losses to which they are relatively more susceptible. I have described one such mechanism: the loss of energy by synchrotron radiation. Another process, and the one originally proposed (*9*) for the depletion in number of electrons, is the Compton scattering by starlight. Let us recall the familiar Compton effect. An energetic photon, such as an x-ray, scatters from an electron of an atom. The recoiling electron picks up energy, and the photon frequency decreases. Energy and momentum are conserved, just as in an elastic collision of billiard balls.

The same fundamental process can occur with an exchange of the opposite kind. A high-energy electron loses energy to the photon, whose frequency increases. The theory of the process is well understood (*9, 10*) and is immediately applicable to cosmic ray electrons moving through a sea of starlight. If the photon energy density is ρ ev/cm³, the average rate of electron energy loss per collision is

$$P_c \cong 2.7 \times 10^{-14} \rho \gamma^2 \text{ ev/sec} \qquad (3)$$

where γ is the same electron energy parameter E/mc^2 as in our previous

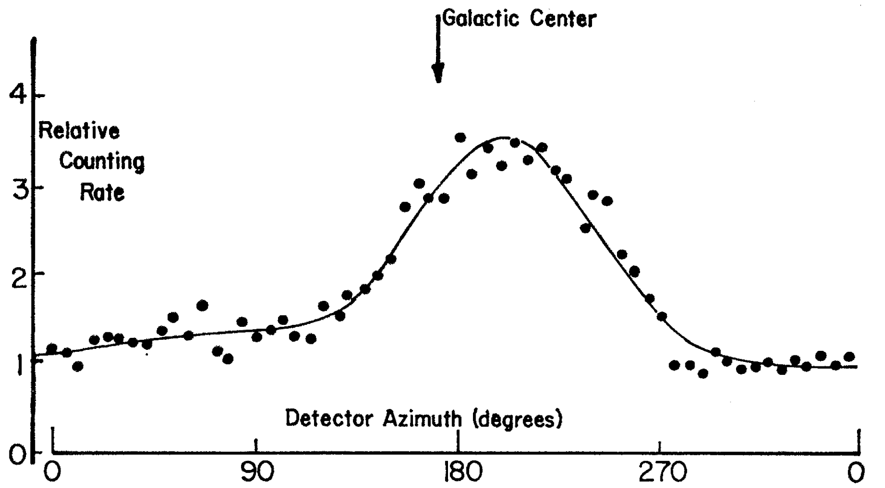

Fig. 2. X-rays detected by counters in a rocket, plotted against angle of spin about the axis of the rocket.

formulas. Taking the typical galactic energy density of starlight to be 1 ev/cm^3, we find a power loss somewhat larger than the synchrotron-radiation loss given by Eq. 2, when we assume a value of about 1 microgauss for the galactic magnetic field.

In this "inverse Compton effect" the loss of electron energy is of course accompanied by a gain of photon energy. We are led to wonder whether recoil photons of this kind can contribute significantly to the electromagnetic spectrum at frequencies above those of the visible region—that is, in the x-ray and gamma-ray regions. The possibility has recently been considered in detail (*11*); I shall mention some broad conclusions.

The spectrum of recoil photons of starlight, in the inverse Compton effect, has its peak at a frequency corresponding to a photon energy

$$E_c \cong 1.8\ \gamma^2 \text{ ev} \qquad (4)$$

Thus, 25-Mev electrons ($\gamma = 50$) produce recoil photons at 5×10^3 ev, in the x-ray region; electrons at 25 Gev ($\gamma = 5 \times 10^3$) produce photons in the gamma-ray region, at 50 Mev. Let us make a crude estimate of the photon flux produced by electrons and starlight in the galactic halo. Take an electron density derived from the observed synchrotron-radiation radio brightness, with a differential spectrum falling as the 5/2 power of the energy. Assume that the velocity distribution of the electrons is isotropic, and that all photons have energies given by Eq. 4 instead of continuous distributions in energy. Finally, assume that the starlight density in the halo is about one-third the local density. Then the flux of recoil photons observed at the earth has the differential spectrum

$$d\phi_c \cong 10^{-4}\ E^{-7/4} dE \text{ photon cm}^{-2}\text{ sec}^{-1}\text{ srad}^{-1} \qquad (5)$$

with E measured in million electron volts. The simplifications and uncertainties of the calculation are such that the coefficient in the formula may be wrong by a factor of 10.

The inverse Compton effect is one process of several that can be expected to produce cosmic electromagnetic radiation at high energies. It is typical of these processes that the predicted fluxes are extremely small. But their detection is of great significance, and it is to this problem that I now turn.

X-rays

Strong absorption in the earth's atmosphere prohibits direct observation of hard photons at sea level, or even at high mountain altitudes. It is necessary to carry instruments to the top of the atmosphere in balloons, or beyond the atmosphere in space vehicles. This difficulty, together with the problem of low intensity, kept us blind for a long time to the high-energy radiation. Much of the experimental work has served only to set upper limits to the flux. Thus, the same early observation (*5*) that bounded the electron intensity also gave a limit for gamma rays.

The first successful measurement (*12*) of cosmic x-rays, carried out with rocket-borne counters, revealed a significant flux of photons with energy around 5×10^3 ev. Figure 2 shows the counter response as a function of angle of spin about the rocket axis. Against a general background flux of 2 photons per square centimeter per second, the counter detected a collimated beam of several times this strength from a source in the direction of the constellation Scorpius. The observation has been confirmed (*13*) by other workers, who give the position of the source at right ascension 16.2 hours and declination −18 degrees. This places the direction of the source in the vicinity of the line of sight from the galactic center. But the slight displacement, apparent from Fig. 2, suggests that the galactic center is not the source of the x-rays in the peak.

If the general x-ray flux, apart from the peak flux, is a real signal, its intensity is of considerable interest. We wonder, for instance, how it compares with the prediction of Eq. 5 for the inverse Compton scattering of starlight. Substituting $E = 5 \times 10^{-3}$ Mev, $dE = 10^{-2}$ Mev (the approximate band width of the counter) into the formula, and taking the solid angle of the detector to be about 1 steradian, we obtain a predicted rate only 1/200 as high as the observed rate. We recall, however, that the prediction took into account only the electrons and starlight photons of the galactic halo. What about contributions to the same process from Compton collisions in the farther reaches of space? An answer to this question suggests itself if we are willing to tentatively accept certain quantitative estimates of cosmological structure.

The radius of the observable universe, given by the Doppler red shift of distant galaxies, is about 10^{28} centimeters. Matter in the form of tenuous gas with density of 10^{-29} g/cm^3 pervades the metagalactic regions. The average speed of the gas is about 500 km/sec; its kinetic-energy density is therefore of the order of 10^{-2} ev/cm^3. This is also, roughly, the energy density of metagalactic starlight, and it is likely that the energy density of metagalactic cosmic radiation does not exceed this value. On the other hand, a lower limit to the cosmic-ray energy density is given by a model in which particles from galactic sources leak into the metagalaxy. This limit is somewhat less than the value for energy density of metagalactic starlight.

If the relative abundance of fast electrons in cosmic radiation is the same for all regions of space, from the local density and the arguments just given we can guess that the value for density of electrons in the metagalaxy is about

1/100 the value for the galactic halo. The starlight density is lower by the factor 1/10. But the distance through the observable universe is greater by a factor of 10^5 than the distance through the galactic halo. Combining these factors, we see that the metagalactic x-ray flux from inverse Compton scattering may be about 100 times the galactic flux. This value is of just the right order of magnitude to account for the isotropic part of the rocket measurements.

A loose end in this pattern of ideas is the requirement that it be consistent with the relatively small radio glow from metagalactic regions. We must be careful not to assume an electron density whose synchrotron radiation is too strong. In order to deal with this point we need an independent estimate of the metagalactic magnetic field: the synchrotron-radiation energy rises, roughly, as the square of the field strength. On the basis of a supposed energy balance between cosmic rays and the magnetic field, we expect a field strength of about 0.1 microgauss. A metagalactic electron density 1/100 the galactic electron density should then produce a radio signal somewhat in excess of the flux from the galaxy. Since it does not appear that such a signal exists, we may have overestimated the electron density or the field strength, or both.

Neutron Stars

I consider now the possible nature of the localized x-ray source in Scorpius. If it is as far away as the galactic center, the source must have an enormous power output, corresponding to more than 100,000 times the luminosity of the sun. This great energy could, of course, be emitted by an aggregate of stars at the galactic center, but the direction of the source is at least 10 degrees away. It is in fact interesting that no unusual celestial object can be seen in this direction in either the radio spectrum or the visible spectrum.

Among the several suggestions that have been made to account for the source, one recent idea (*14*) is extremely interesting. It is a model for the development of supernovae, involving the collapse of a massive star. If the mass of the stellar core during collapse exceeds a certain limit, the explosion results inevitably in the formation of a *neutron star.* This is an object of tremendous density, with a radius of only 1000 kilometers and a mass about equal to that of the sun. The density is of the order of 10^{15} g/cm^3, representing the closest possible packing of atomic nuclei. Following collapse, the surface properties of a neutron star depend on its internal temperature, which is typically in the neighborhood of 10^9 degrees Kelvin. At this internal temperature the total thermal energy is 2×10^{59} ev, the luminosity is 5×10^{48} ev/sec, the photon spectrum has a peak at 4×10^3 ev, and the lifetime for emission is 1700 years. The star is undetectable except in the x-ray band.

Can the x-ray source in Scorpius be a neutron star representing the remnant of a supernova? The photon flux at the earth carries an energy of 10^5 ev cm^{-2} sec^{-1}. From the law of inverse squares we infer that a source with the luminosity given by the model would produce this flux at the distance 2000 light-years. The initial visible brilliance of a supernova at this distance should be considerable—about one-fourth the brightness of the moon. Now the object reported by Arabian astronomers for A.D. 827 appears to be an appropriate candidate, although recent historical research suggests that it was a comet. Its position was rather precisely the same as that indicated by modern observation for the x-ray source in Scorpius, and its initial brilliance was compatible with our estimate.

Another possible instance of a neutron star may be the supernova remnant we now see as the Crab nebula. Here it is possible to measure the distance of the object, from observations of its visible features; the current estimate is about 4000 light-years. If there is a neutron star at the center of the Crab, with an intrinsic x-ray luminosity similar to that of the source in Scorpius, the flux of hard photons at the earth should be about 2×10^4 ev/cm^{-2} sec^{-1}. The rocket experiments have in fact revealed an x-ray flux of this magnitude from the approximate direction of the Crab.

It is possible that we are on the threshold of an era in x-ray astronomy in which a large number of sources will be studied in detail. The astrophysical information contained in such observations is considerable. Suppose, for instance, future measurements give x-ray spectra with good resolution. We shall see characteristic discontinuities at the ionization energies of K and L electrons at the surface of the source. If the neutron star hypothesis is correct, the gravitational red shifts of these lines will be large and easily measured. The shift depends on the mass-to-radius ratio of the star. But the relation between mass and radius can be independently obtained from the theory of elementary particles. Thus we shall have values for the two parameters, and from these, values for the intrinsic luminosity of the star. The measured flux will then give the distance, serving in at least some cases as a check against other knowledge on supernova remnants.

Gamma Rays

Let us consider next the production and detection of gamma rays, the photons whose energies begin at about 1 Mev and cover a broad spectrum whose upper limit is not yet known. Gamma rays at the low end of this spectrum are produced in great abundance by nuclear reactions inside stars. The sky would be bright in radiation of this kind were the radiation not effectively trapped in the interiors of the stars themselves. Only in unusual circumstances does a normal star emit large numbers of photons at high energy. Major solar flares, for instance, are accompanied by the emission of gamma rays. During the class II flare of 20 March 1958, a counter experiment (*15*) in a balloon at high altitude revealed a brief gamma-ray burst with photon energies around 3×10^5 ev and an intensity of 10^7 ev cm^{-2} sec^{-1} at the earth. The observers interpreted the gamma rays as the result of a process called bremsstrahlung, in which high-speed electrons radiate photons while slowing down as a result of atomic collisions. By assuming that about 1 percent of the flare energy went into 1-Mev electrons which subsequently emitted bremsstrahlung from the solar photosphere, one can account not only for the gamma rays but also for the very intense radio bursts observed during the flare. The radio signal would be synchrotron radiation from the same electrons circulating in a magnetic field of about 1000 gauss.

Except for the sun, no localized source of low-energy gamma rays has so far been detected. Flare-type bursts from other stars are probably common, but far too faint to be seen even in the nearest stars. But just as the solar flares produce gamma rays in association with radio signals, any strong

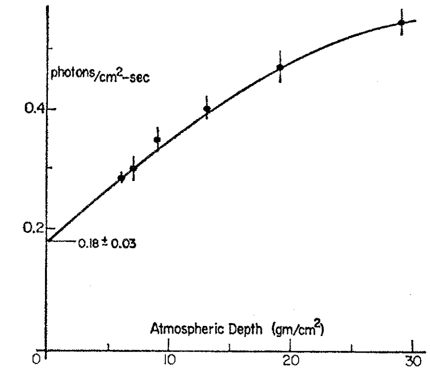

Fig. 3. Dependence of 0.5-Mev gamma radiation on thickness of air near the top of the atmosphere.

radio source, we might suspect, may also be a source of gamma rays. Our knowledge of some of the radio sources is complete enough to suggest models for the production of high-energy radiation. For example, it has been proposed (*16*) that the original energy of the Crab supernova was largely supplied by spontaneous fission of $_{98}Cf^{254}$. If it was, there must be several long-lived nuclear emitters of gamma rays still active in the nebula, with photon energies of several hundred thousand electron volts. According to two independent estimates (*17, 18*), the flux at the earth is of the order of 10^{-2} γ cm^{-2} sec^{-1}, and it should be detectable by modern instruments above the atmosphere.

A gamma-ray line at 0.5 Mev arises from the annihilation of positron-electron pairs. It has been suggested (*19*) that certain anomalous extragalactic radio sources, such as M 87 and Cygnus A, derive their great intensities from annihilation of matter and antimatter. A model of the Cygnus source as a pair of colliding charge-conjugate galaxies led one author (*17*) to estimate that the flux of 0.5-Mev photons should be 0.1 to 1 γ cm^{-2} sec^{-1}. Such a rate is high enough to be measured easily, especially if the detector has good angular resolution.

An experiment (*20*) designed to measure the flux of 0.5-Mev gamma rays has recently been carried out near the top of the atmosphere. The flux at a depth of 6 g/cm^2 is about 0.3 γ cm^{-2} sec^{-1}, and the extrapolation to zero depth (Fig. 3) gives a residual of about 0.2 γ cm^{-2} sec^{-1}. Since the detector was nondirectional, it could not distinguish between a downward extraterrestrial flux and an upward albedo of secondary photons from cosmic rays interacting with the atmosphere. The result can only set an upper limit, of a few times 10^{-2} γ cm^{-2} sec^{-1} $srad^{-1}$, for the extraterrestrial flux averaged over the sky. Both the sun and the Crab nebula made high-elevation transits of the meridian during the balloon flight. The absence of time variations in the counting rate sets an upper limit of 0.1 γ cm^{-2} sec^{-1} for the 0.5-Mev flux from each of these sources.

Extraterrestrial gamma rays in the same energy region have been reported from a recent experiment (*21*) on the moon probe Ranger III in January 1962. The instrument was far enough from the earth to eliminate the albedo contribution, and an in-flight check was made against secondary radiation from the spacecraft. Figure 4 shows the differential energy spectrum of gamma rays averaged over the sky. Several aspects of the observation are interesting. The absence of significant peaking at 0.5 Mev sets an upper limit of about 10^{-3} γ cm^{-2} sec^{-1} $srad^{-1}$ for the general sky glow resulting from positron-annihilation radiation. Above 1 Mev there appears to be a flat spectrum, difficult to explain if it is not an instrumental artifact.

The spectrum below 1 Mev has a shape consistent with the energy dependence expected for inverse Compton scattering: the flux is, roughly, 2×10^{-2} $E^{-7/4}$ γ cm^{-2} sec^{-1} $srad^{-1}$ with E measured in million electron volts. But, just as in the case of x-radiation, the intensity is 200 times greater than the prediction of Eq. 5 for scattering in the galactic halo alone. Thus we gather more support for the idea that high-speed metagalactic electrons make a contribution to the process.

Higher Energies

The next interesting region of the electromagnetic spectrum is in the neighborhood of 100 Mev. Its importance arises principally from the fact that neutral pi mesons (π^0), produced by nuclear collisions of cosmic rays, decay into photons of about this energy. The lifetime of the neutral pi meson is so short that the decay photons travel to us directly from the source of the original collision. Thus their detection permits us to probe the combined densities of cosmic rays and of matter, integrated along the line of sight into space. Once again, however, the observer who wishes to investigate this part of the spectrum faces formidable obstacles. Fluxes are small, present detectors have low efficiency and poor angular resolution, the photon energy cannot be measured with precision, and instruments must be flown above the atmosphere.

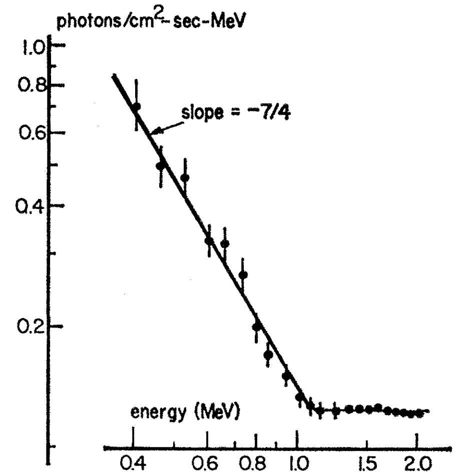

Fig. 4. Differential spectrum of low-energy gamma rays observed on the space probe Ranger III.

As an example of the fluxes to be expected from the decay of neutral pi mesons, we consider the interaction of galactic cosmic rays with interstellar hydrogen. If the local cosmic ray flux is typical of the entire galaxy, we can use it to estimate the rate of π^0 production per hydrogen atom:

$$q_o \cong 5 \times 10^{-27}\ \pi^0\ sec^{-1}\ srad^{-1}\ atom^{-1} \tag{6}$$

Each meson decays into two photons. The hydrogen thickness along the line of sight to the center of the galaxy is roughly 10^{22} atoms per square centimeter. Thus the photon flux from this direction should be of the order of 10^{-4} γ cm^{-2} sec^{-1} $srad^{-1}$.

Do other physical processes compete with π^0 decay in this region of the spectrum? We recall that inverse Compton scattering in the metagalaxy may be feeding in photons of lower energy at the rate of 2×10^{-2} $E^{-7/4}$ dE γ cm^{-2} sec^{-1} $srad^{-1}$. If such a spectrum extends to the higher energies, the total flux above 50 Mev is roughly 10^{-3} γ cm^{-2} sec^{-1} $srad^{-1}$—a value larger by an order of magnitude than the predicted contribution from galactic mesons. And there is another possible source: the bremsstrahlung of galactic electrons in collision with interstellar matter. An estimate of this mechanism gives a flux of several times 10^{-4} γ cm^{-2} sec^{-1} $srad^{-1}$ from the direction of the galactic center.

Neutral pi mesons are born not only in cosmic ray collisions but also in the course of an annihilation process. Suppose the galaxy contained n antiprotons per cubic centimeter as a small admixture with the one proton per cubic centimeter characteristic of ordinary matter. The rate of gamma-ray production from annihilation would be of the order of $10^{-15}\ n\ \gamma\ cm^{-3}\ sec^{-1}$. According to a particular cosmological argument, the value of n would be about 10^{-8}. The annihilation mechanism then gives rise to a flux of about $10^{-2}\ \gamma\ cm^{-2}\ sec^{-1}\ srad^{-1}$ from the direction of the galactic center.

The estimate for antiproton density comes from a modification (*19*) of a steady-state cosmological model (*22*) of the expanding universe, in which protons and antiprotons appear spontaneously at equal rates. Steady-state cosmology requires creation at the rate of $3\ \rho/T$, where ρ is the average density of matter and T is the time required for light to cross the universe. Using accepted values for ρ and T, and adopting a charge-symmetric model, we expect antiprotons to appear at the rate $10^{-23}\ cm^{-3}\ sec^{-1}$. Now the lifetime for annihilation in the galaxy is short enough so that the creation rate is in equilibrium with the annihilation rate, the latter being about $10^{-15}\ n\ cm^{-3}\ sec^{-1}$. The two rates are equal when $n \cong 10^{-8}$ antiproton per cubic centimeter.

Although several groups of workers have engaged in the search for cosmic gamma rays in the 100-Mev region, none has so far succeeded in detecting them in a way that is completely free from uncertainty. The first experiment (*23*) in which counters of modern design were taken to the top of the atmosphere set an upper limit of $7 \times 10^{-3}\ \gamma\ cm^{-2}\ sec^{-1}\ srad^{-1}$ for the flux averaged over the northern celestial hemisphere. None of the production mechanisms discussed above could be ruled out by this observation, but it showed that there is no unforeseen process of great intensity.

A sophisticated telescope with gamma-ray counter operated in the satellite Explorer XI for 5 months in 1961. The first report (Kraushaar and Clark, *24*) of the experiment, based on 22 selected counts, suggested that there is a real flux of about $5 \times 10^{-4}\ \gamma\ cm^{-2}\ sec^{-1}\ srad^{-1}$ averaged over the sky. But subsequent study (*25*) led to the suspicion that the detector may have been looking at gamma rays from the atmosphere. Kraushaar and his co-workers now feel that the flux previously reported can only be taken as an upper limit. The result is nevertheless of some interest. For example, while not necessarily vitiating the entire steady-state cosmological model, the fact that the limit is less than 1/20 of the prediction implies an error in estimating at least one of the parameters of the model.

Search for Anisotropies

It is difficult to correct with assurance for all forms of background in these experiments; the task of detecting a small isotropic flux of gamma rays is therefore formidable. Less ambiguous, however, would be the detection of anisotropies in the flux. Now, gamma radiation produced by interaction of galactic cosmic rays should be seen mainly from the direction of the galactic disk. There may, of course, also be point sources of the high-energy flux, just as there are point sources for other parts of the spectrum.

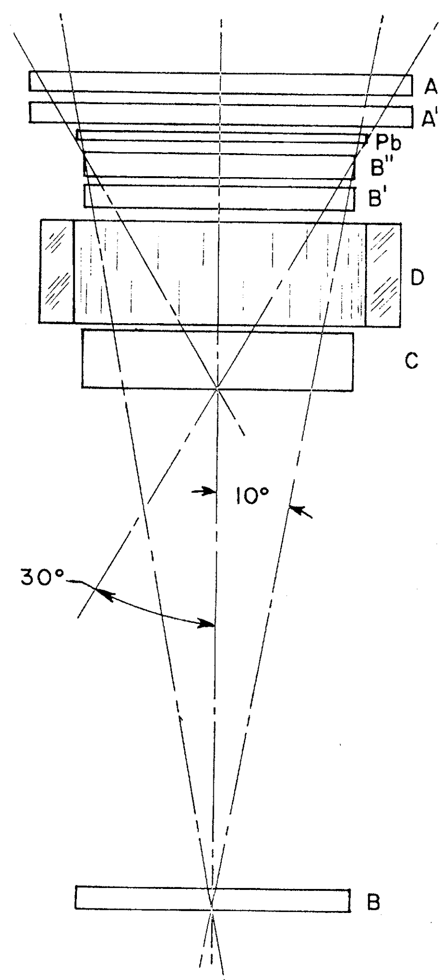

Fig. 5. Schematic diagram of the counter for measuring high-energy gamma rays. It was flown by the Rochester group in September 1963.

I have been working for several years with a group whose aim has been to measure the isotropic gamma-ray flux in the 100-Mev region and, at the same time, to search for anisotropies. Part of the program has been the development of appropriate counter techniques. One instrument (*26*), designed to be flown in high-altitude balloons, is a compact detector in which we achieve good angular resolution by exploiting the geometrical properties of Cerenkov radiation. Counters of this type were flown successfully (*27*) in July 1961, April 1962, September 1962, and October 1962. More recently, in order to increase our knowledge of instrumental background effects, we have made two flights with the counter system shown schematically in Fig. 5. To be recorded as a gamma ray in this system, an event must trigger scintillation counters B'' and B' and the Cerenkov counter C; it must not trigger scintillator A'. We can require anticoincidence with the ring scintillator D, in order to reduce background effects of particles entering from the side. When the event also triggers B it is assigned to the narrower cone of sensitivity. Finally, we derive a "true" rate by subtracting the rate obtained with the sheet of lead removed, hoping in this way to count only the events that generate electron pairs in the sheet. The counter is flown with its axis toward zenith.

Data from our early flights indicated the dependence of gamma ray rate on altitude which is shown as set a of Fig. 6. The flux extrapolated to the top of the atmosphere is roughly $5 \times 10^{-3}\ \gamma\ cm^{-2}\ sec^{-1}\ srad^{-1}$. The more recent flights, in which the counter of Fig. 5 was used, gave us sets b and c, with extrapolated fluxes that are significantly lower. We do not yet understand these differences. Did the new detector discriminate against background events that are somehow generated by cosmic rays in the lead sheet? Or did we reduce the efficiency for detection of a true gamma-ray flux? Only by further exploration can we resolve the problem.

Since our balloons are aloft for a long time, the detector scans an entire circle of the sky at constant declination. The latitude for all our flights has been close to 30°N. In the polar plot of Fig. 7 the extrapolated gamma flux is plotted against right ascension; in Fig. 7 the results of several flights are combined. There appears to be an enhancement of the flux in the region of

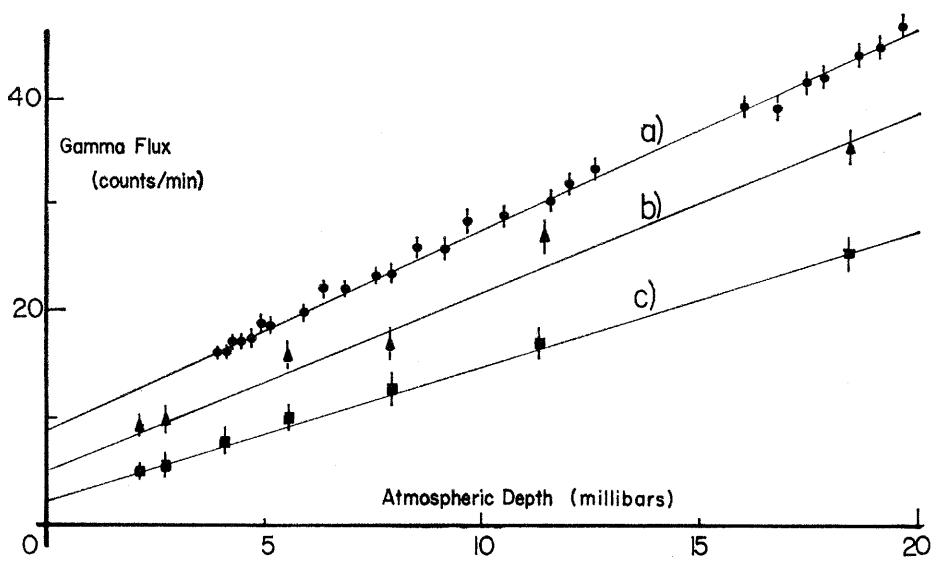

Fig. 6. Dependence of counting rates for high-energy gamma radiation, in a 30-degree cone, on thickness of air near the top of the atmosphere. Data for set *a* are from four early flights (*27*); data for set *b* are from the counter of Fig. 5 with the guard ring *D* not operating; data for set *c* were obtained by rejecting events that trigger *D*.

right ascension around 20 hours. Now this is the direction of a segment of the galactic plane; it is also the right ascension of the strong radio source in Cygnus, whose declination is within 10 degrees of latitude 30°N. It may be, therefore, that the detector has seen high-energy gamma rays from one or the other of these sources. However, there is a chance that the effect is associated with time of day. All the flights took place at the same time of year, with galactic transit occurring shortly after sunset.

The satellite S-16, launched in March 1962, was the first orbiting solar observatory. It contained several gamma-ray detectors, including a high-energy counter system designed in our laboratory (*28*). The axis of this instrument swept out a great circle in the sky, divided into 16 angular sectors. One sector contained the sun. Thus it was possible for us to compare the flux of solar gamma rays with general sky glow. Two major solar flares occurred within several weeks of the launching but gave rise to no significant increase in counting rate above the background. In both these events the gamma flux was less than 10^{-2} γ cm^{-2} sec^{-1} for photon energies above 100 Mev. Observations of the quiet sun, averaged over many orbits, indicated that the steady flux cannot exceed 10^{-3} γ cm^{-2} sec^{-1}.

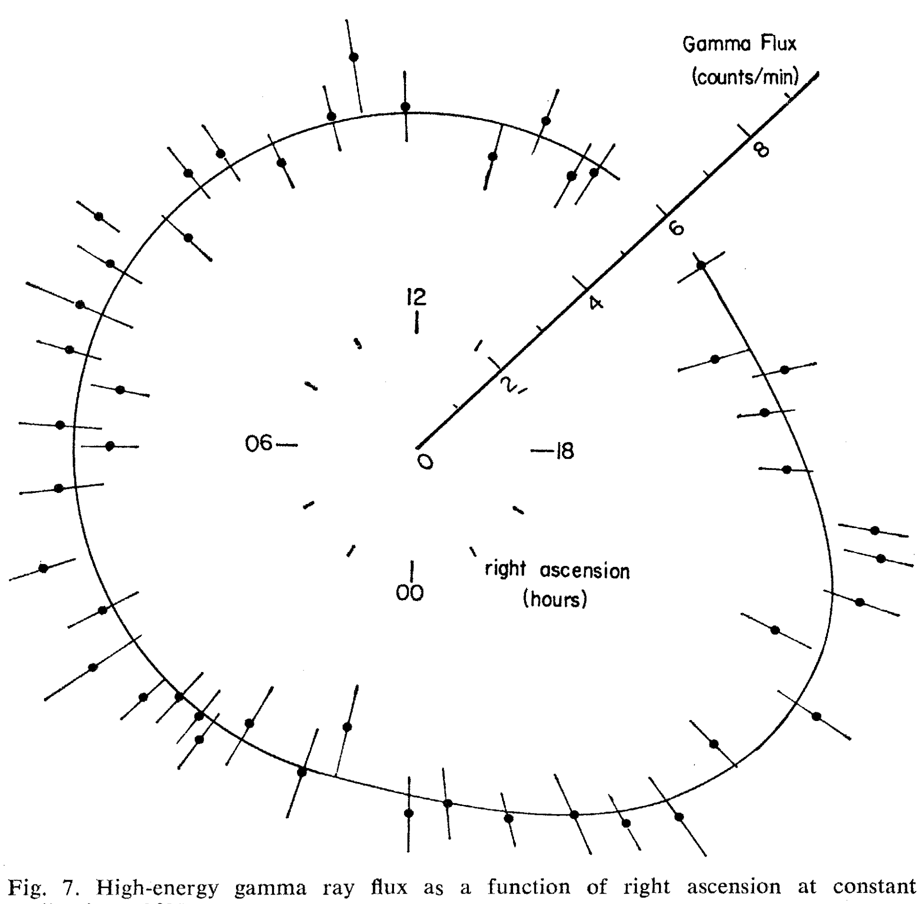

Fig. 7. High-energy gamma ray flux as a function of right ascension at constant declination 30°N.

Rare cosmic rays of extremely high energy, at least as high as 10^{20} ev, reveal themselves by generating extensive showers of secondary particles in the atmosphere. Do photons occasionally contribute to events of this class? The answer is currently not known. No anisotropy associated with strong radio sources has been found, and not enough is yet understood about the mechanism of shower production to permit selection of gamma-ray-initiated events from the overall flux. But progress in this field is rapid, with laboratories in many parts of the world contributing to the study. Their work will extend our knowledge of the electromagnetic spectrum to the highest energies of all.

Summary

Within a few decades astronomy has extended the compass of its observations from the visible spectrum downward to radio waves and upward to the highest energies known to science. The major new accomplishments are in the radio and x-ray bands, and in the associated study of cosmic ray electrons. Synchrotron radiation is known to be a mechanism for radio signals; discrete x-ray sources have been found; the intensity and the charge ratio of galactic electrons are under study. Experimental results at energies above the x-ray region are less firm. The sun surely emits gamma rays at energies of about 1 Mev during flare activity, and instruments in deep space have probably recorded the general galactic glow of similar photons. Upper limits for fluxes have been set at 100 Mev and beyond.

To some extent the physical processes which give rise to the extraterrestrial

radiation are familiar to workers in the terrestrial laboratory. Synchrotron radiation is an example; the bremsstrahlung of electrons, the production of neutral pions in *p-p* collisions, and the annihilation of electron and nucleon pairs are others. Some proposed mechanisms are, and perhaps always will be, purely speculative in the sense that they are not directly observable in the laboratory. The inverse Compton effect, possibly one of the sources of a metagalactic sky glow of hard photons, is in this class. There is little chance that spontaneous creation of matter, even if it occurs in nature, can be observed on a terrestrial scale. And the extreme physical conditions proposed for neutron stars are beyond our ability to reproduce. Only through interpretation of astronomical data can we test the validity of these ideas. The many pictures of the universe given by the vast electromagnetic spectrum are essential to the synthesis of our concepts.

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Our Heritage from Galileo Galilei

Galileo's refusal to rely on authority for scientific truth is a principle we may be in danger of forgetting.

R. E. Gibson

This year we celebrate the 400th anniversary of the birth of two men: William Shakespeare, playwright, of London, and Galileo Galilei, gentleman, of Florence. Both of these men were discerning students of human experience, masters of expression who wove the material they gathered into artistic forms that captivated the interest and excited the admiration of their fellows. Both enjoyed a full measure of recognition and acclaim from their contemporaries.

However, it is hard to find further resemblances between these two men or between the legacies they left the world. Shakespeare stands in history as the supreme product of an age; the fruits of his genius represent the pinnacle of an art—the art of portraying human nature at its noblest and at its weakest through the vehicle of the English language on the dramatic stage. His works are read by every schoolboy today and loved by all devotees of the drama and students of human nature.

Galileo, on the other hand, was a pioneer who blazed the trail to a new age, whose thought, action, and writing laid the foundations for a revolutionary approach to an understanding of nature, and, later, of man. So well were these foundations laid that succeeding generations have built upon them the elegant and viable structure called modern science. Galileo's books are not widely read today; his immortality resides in the growth of our understanding of the world around us.

There is another important point of difference. We know little about the inner life of William Shakespeare; little of the man himself shines through his writings. In contrast, Galileo's writings reveal his mind and soul, his vanity and his wisdom, his humor and his petulance, the ideas and ideals that guided his thought and conduct.

We have, therefore, the opportunity to examine the ideas and principles of one who had to fight to overthrow an outworn academic establishment and to demonstrate to the intellectual world the power of methods we now take for granted. We can compare his principles and practices with our own to see whether modern science is surviving the effects of power and prestige any better than did the system it replaced.

Galileo was born at the right time and in the right environment. This statement may strike many as strange in view of the hidebound outlook of the Italian schoolmen and the attitude of the church. Yet it is hard to find another environment anywhere at that time in which universities such as Padua existed and where wealth was allied with taste and appreciation of genius of all kinds. It was an arena in which Galileo's gifts for the dramatic could find full scope.

Galileo also inherited natural gifts which, appropriately cultivated, endowed him with great intellectual capacity, mechanical ingenuity, artistic taste and skill (he excelled in music and in painting), outstanding powers of expression and, I believe, a sense of humor. He was a man who could have won recognition and fame in almost any walk of life, but who was irresistably drawn to the study of mathe-

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