GRAVITY INSUFFICIENT

By HAL CLEMENT

For centuries after Newton, men thought that gravity, singlehanded, ruled the Universe. Now . . . we're learning about the stupendous magnetic forces actually at work—of magnetic explosions measurable not in megatons of TNT, but megabombs of hydrogen bombs!

MY IMAGINATION is not a very estimable character. He's an artist without being a craftsman, which is almost immoral; he's lazy; and he's sneaky.

He's an artist because he paints pictures. He's not a craftsman, because unless he is closely and rigidly watched the pictures won't follow rules—rules of art or of nature or even of plain consistency. He's lazy and sneaky because he leaves out essential details from his pictures whenever I'm not watching to point out that they should be there.

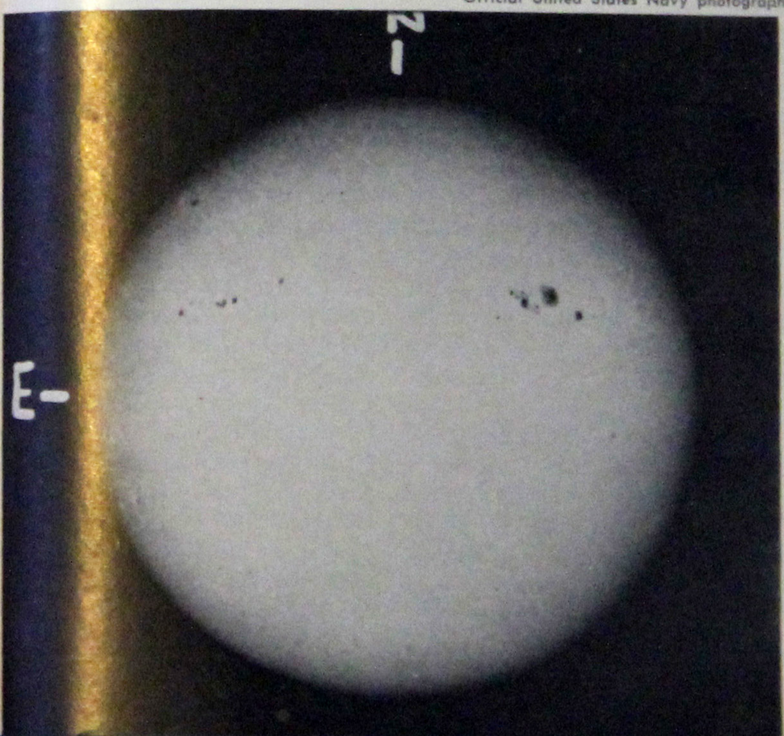
In addition, he's a bit on the incompetent side. He doesn't really create; he reassembles things from my memory, and if other people can't see where they came from he feels he's done something smart. When he can't do a job at all, he sulks.

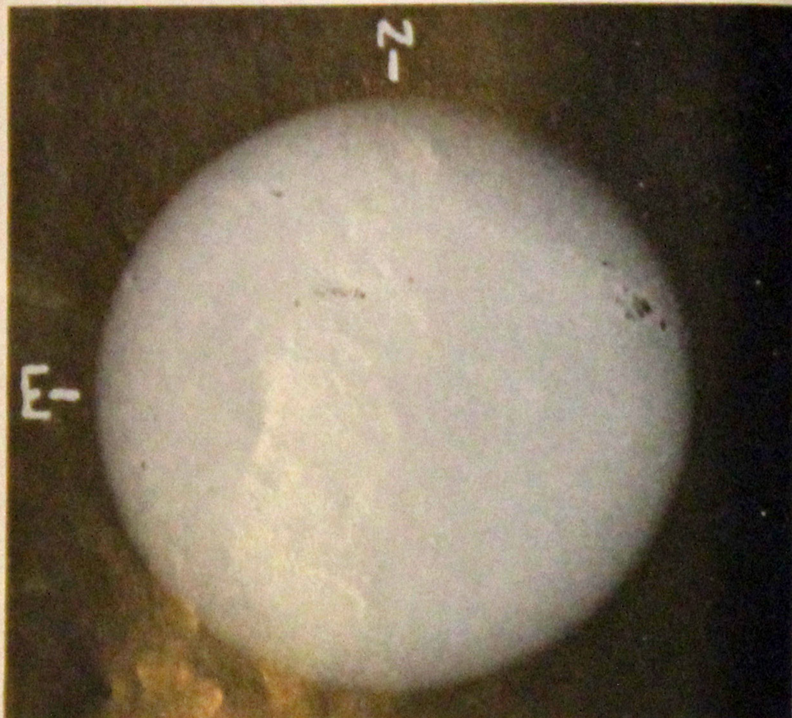
For example, he can't do a thorough job on the picture of a rocket taking off, because some of the essential data is not to be found in my memory. It's a little embarrassing for a science-fiction writer to admit that he has never seen first hand the blast off of a large rocket, but it's true in my case; all my imagination has to work on is a collection of movie and television scenes.

Now, there's a fair amount of detail in those memories; he can paint a good visual picture, I guess. (How can I be sure?) It shows that flakes of frost shedding away from the hull around the liquid oxygen tank as the airframe trembles to ignition shock, the cloud of steam from the water spray in the blast pit, the column of incandescent gas marked with shock diamonds as the great metal cylinder eases its way upward from the pad. It shows the hasty, here-and-there hunting of the fire tongue as the gimbaled motor responds to commands from the guidance device to keep the machine vertical, the blue of the background sky and the white and gray of its clouds, and the vast column of white smoke being slowly twisted by the winds until it no longer marks the course of the departed rocket. I can see all these things in my imagination's picture; but I can't feel the ground tremble as the blast first cuts loose—I'm not even sure that it does. I can't hear the thunder of the gas stream; what I've heard in theaters and in my living room is a pale, shadowy imitation. The electronic system that can record and reproduce that sound hasn't been made yet. Even gunfire doesn't really come through—I know at least one person who enjoys TV westerns

The sun is the only star in the Universe that we can observe in close detail . . . and that's not easy! This shot, taken in white light, was made March 15, 1958.

Official United States Navy photograph





Official United States Navy photograph

This one, also white light, was taken two days later—March 17, 1958. The rotation of the sun, and some change in the easterly sunspot group can be clearly seen.

but won't willingly go near a shooting gallery because of the noise—and gunfire doesn't begin to approximate the sound of a rocket exhaust, I'm told.

I can *guess* what I'm missing, of course, and that's how I know the imagination is lying down on the job. My memories do have records of some fairly loud noises. They include the environment of a B-24 cockpit when bomb doors and flight deck hatch were open and flak was bursting close enough to be heard above the propellers. They include the time dirt was being dumped down my neck by the sound wave from a forty kiloton nuclear blast four thousand yards away—the authors of physics books who claim that the actual displacement of air molecules in a sound wave is negligible aren't considering sound waves with a pressure peak of several pounds per square inch and a half-cycle time of over a second. There's quite a breeze during that second. The same blast set the desert rocking under my feet with a set of ripples remarkably like those on a pond disturbed by a stone. It's a little disconcerting to have a trench which has been dug in hard soil seesaw like a raft in the wake of a speedboat; I remember it vividly. I can guess, therefore, that I'm missing a good deal from this rocket takeoff picture; but I can't *know* what I'm missing. My imagination isn't competent for the job.

At that, it may not be entirely his fault. I'd miss a good deal even if I were actually in the blockhouse and all my senses were on the job. I could see, hear, feel, and smell, but it's no news to anyone reading this magazine that those four senses don't cover a very wide band of phenomena. The radiation of four to eight thousand Angstrom electromagnetic photons; the broadcasting of atmospheric pressure waves at about all frequencies and energies which the properties of the air itself will permit; the transmission of shock waves to and through the solid ground; the fouling of the air with partly decomposed hydrocarbons and/or hydronitrogens—is that all that's going on? Not on your tintype. That's merely all I'm personally equipped to detect.

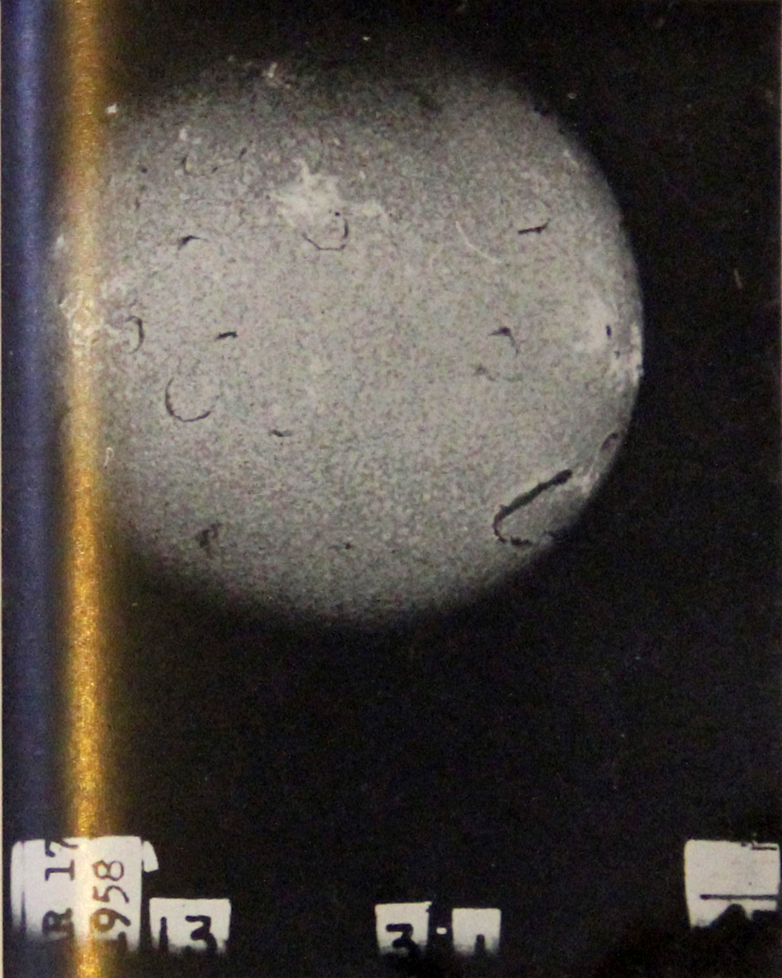
Now that's a major disadvantage, because I'm supposed to be not merely a science-fiction writer but a science teacher, and it's my business not merely to admire the pictures my imagination paints but to transmit them as completely as possible to other people. If my own pictures are incomplete, how can I or anyone who listens to me possibly understand what's really going on—and more important, why it's going on?

My sloppy imagination has gotten away with a lot, there, for a good many years. Maybe there's some excuse. Like every other scientist, an astronomer works from incomplete data; but in his case the incompleteness is due not merely to his personal sensory limitations but to the sheer distance from the things he's studying, coupled with the rotten conductivity of the intervening medium. About all space will transmit is electromagnetic radiation. Until recently, I never thought of a single astronomical factor in terms of anything but light. And that is bad.

For example, half a dozen times a year I aim a five and a half inch telescope at the sun, set up a white paper screen behind the eyepiece, and spend three quarters of an hour trying to account for the details on the screen to a group of ninth graders. We can see a disk of light, visibly less brilliant away from the center and trembling noticeably at the edges. Usually we can see a number of small dark patches with not-quite-so-dark rims around them. If we look closely, we can see large, very irregular patches which are somewhat brighter than the general disk—these show up best near the edges. That's it. That's what distance, the natures of the intervening media, and our

The pictures on pages 86, 87, 88 and 89 are from an automatic monitor system; each frame is dated and timed to the second. This sequence occurred on March 17, 1958—and compare them with the white-light picture of the same date! These were taken through a very narrow-pass filter, by the light of the hydrogen Alpha spectrum line. On the west (right) limb of the sun, in the course of these four minutes, a "small" flare (10,000 miles perhaps?) erupts a pimplelike excrescence, and collapses.

Official United States Navy photograph



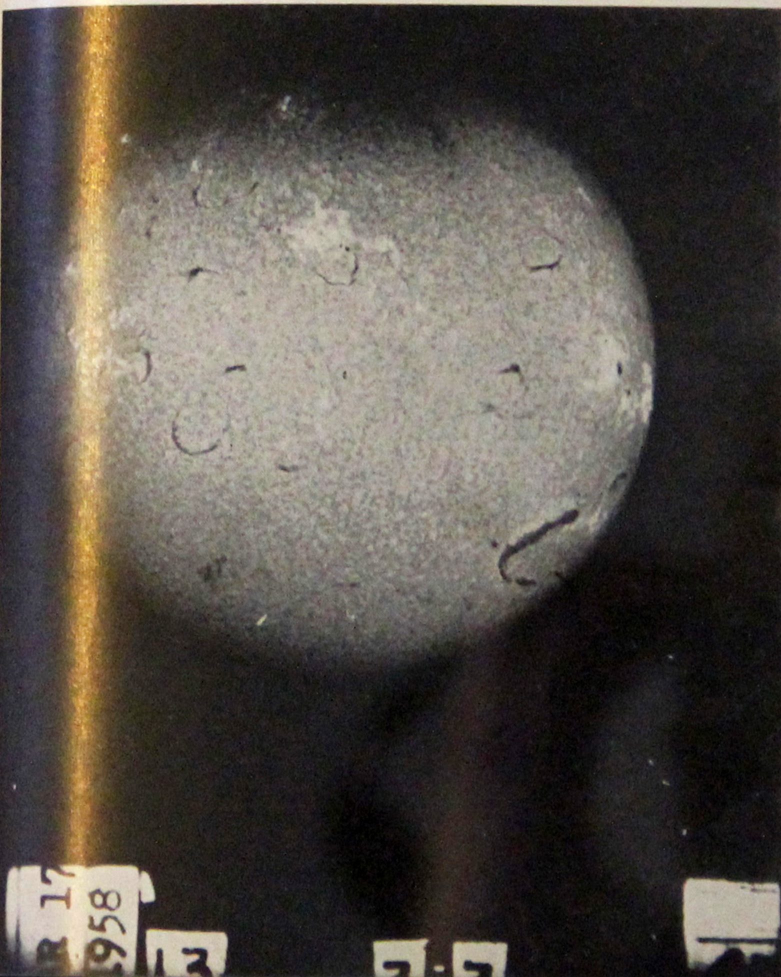
sensory and instrumental limitations let us see. We hear, feel, and smell nothing, unless some youngster with more humor than sense puts a pencil or notebook cover right behind the eyepiece.

Years ago my imagination painted a picture of the original of that image—and he's gotten away with it all that time, even though it's a *silent picture!* Worse, I've been passing that picture on to my students. I can give reason for that, but not an excuse. I simply was never impressed with a noise-image even in the days when sunspots were described as solar tornadoes. The bubbling "rice grains" that show on the best photographs—my little instrument can't make them out—and the glowing faculae; the

prominences swirling, floating, fountaining upward and raining downward out of nothingness; I saw them first on silent films, and silent they've been to me. The rumbles and whistles from the radio telescopes didn't impress me as real sound, just as an arbitrary translation of impulses which didn't result from the action of a microphone at the other end. They were just as arbitrary, those noises, as the wiggles recorded on graph paper by the present equipment; and the wiggles are easier to scan and interpret than memories of changing sound, though the sounds I suppose are really just as meaningful. It was a ghostly, silent sun to me, and I'm ashamed of my imagination. (1, 2)

Others had different pictures. John

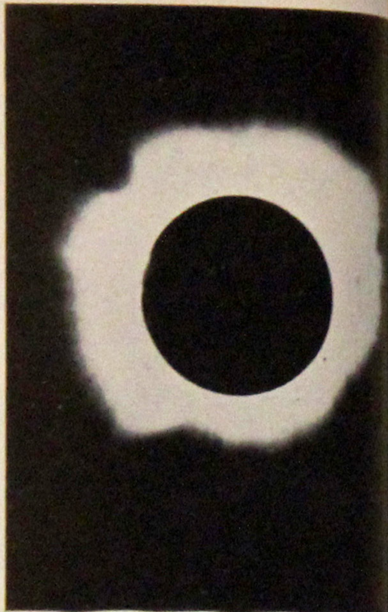
Campbell writes, and apparently thinks, of the stars as "roaring furnaces of the cosmos." It's not just a figure of speech, either. Stars are made of matter, the matter has a pressure which can vary and a temperature which can vary and what else does sound need? If I'd been properly alert, I could have held any of a score of physics texts in front of my imagination's bleary eyes and swished a cat-o'-nine-tails until he'd added a sound track to the picture. Could have done it years ago, I mean; it's done now. However, now that I realize just what the loafer has been getting away with, I'm going to keep after him. I'm dragging him out of his lotus-eater's paradise and driving him back to the sun to redo his picture from the canvas out; and if the old high school and college physics texts



will be of any use, they're standing by.

Of course, we can't let the poor fellow just paint. He has to be guided; so we'll start him out from a well equipped observatory—one with gear which can make a nice, big, detailed solar image in any of a reasonably wide choice of wave lengths, is high enough up on a mountain to have the worst of the atmosphere below it, has short-wave radio equipment both for communication with other observatories and ionosphere research of its own, and is in communication with a widespread group of stations all equipped to detect temperature changes, magnetic changes, high energy particles, and anything else some imaginations which have been more on the job than mine have dreamed up.(6) Given all this equipment, let's ride along to the sun with our chastened imagination, and really *look.* And listen.

Even if we don't bother to select wave lengths but merely look in white light, we can see a lot of detail as we swoop toward the sun and come to rest a couple of thousand miles above the photosphere—the "surface." The sunspots are obvious, with their moderately cool penumbrae sloping gently down toward the really chilly—say, forty-seven hundred Kelvin—umbrae. The granules are clearly visible as bright humps a few hundred miles across, perhaps a hundred degrees or so hotter than the surrounding photosphere. The imagination, being lazy, is fond of these "rice grains;" it's easy to picture them as



The very brilliance of the sun makes observing it difficult. The sun's corona used to be visible for study only during total eclipses. This United States Navy photograph was taken June 8, 1937, by setting up equipment on Canton Island . . . and then having good luck with the weather.

the tops of small convection currents. They are quick-change artists, losing their identity completely in ten or fifteen minutes.(2, 11, 29)

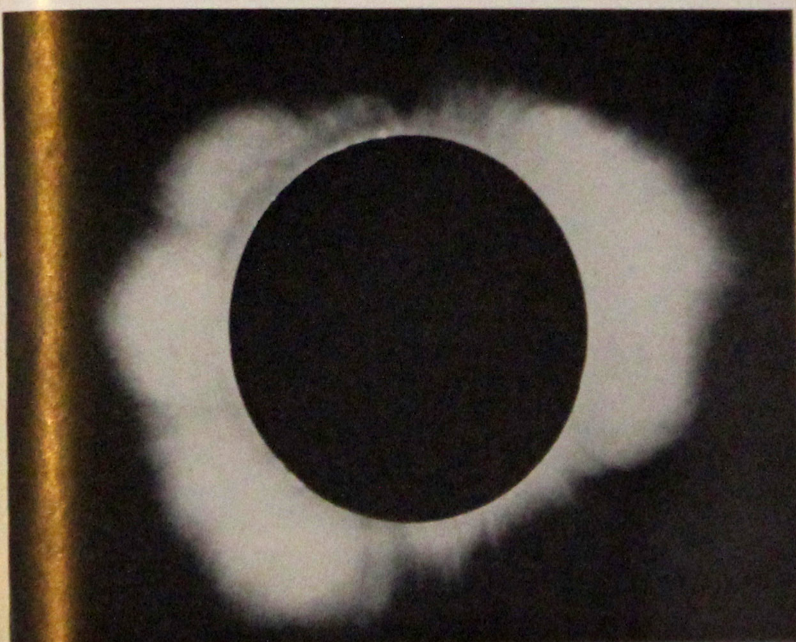
The faculae are also brighter, but on a different size scale; they are thousands of miles across—sometimes tens of thousands. They seem to hump up a trifle above the general "surface," and *maybe* they, too, represent the tops of convective masses; their much longer lives, as compared to the granules, may be just a consequence of greater size.

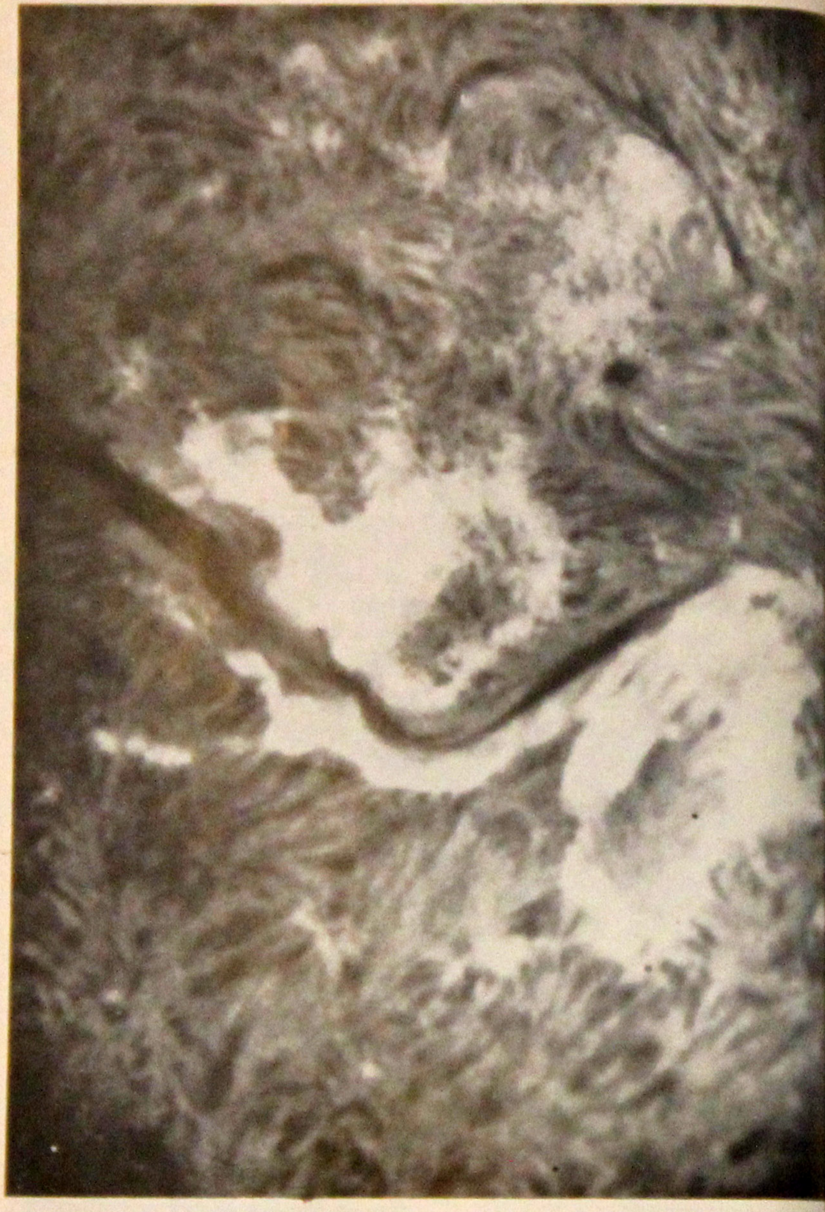
We can see the spicules, "baby" prominences flashing upward for a few thousand miles during their brief lives, which compare with those of the rice grains, but we find we can see these better if we are more selective in the wave lengths we use for observation. If we pick a nice, narrow band around one of the hydrogen wave lengths, we find we can really see prominences; and they're fascinating things to watch.

Gigantic clouds of hydrogen float motionless here; form shifting, wavering, dancing pillars and columns and fountains and curtains in other places; blasting upward in some spots, hurtling or drifting or raining downward in others—with the downward motions seeming to predominate, at least if we do our observing in hydrogen-alpha light. Presumably hydrogen is going up in some form to keep up the supply that comes down, but if so, few of its atoms during the upward trip are in condition to make electron swaps between the second and third quantum levels. We'd have to use some other wave length to see them, if they're either radiating or absorbing at all.(9, 14)

The whole medium is thin, of course—a few thousandths as dense as Earth's atmosphere at sea level—but it is hot, it is material, and the imagination with a sheepish expres-

This far more detailed picture was taken at the High Altitude Observatory, at Climax, Colorado, on November 19, 1949—using a coronagraph, which artificially eclipses sun.





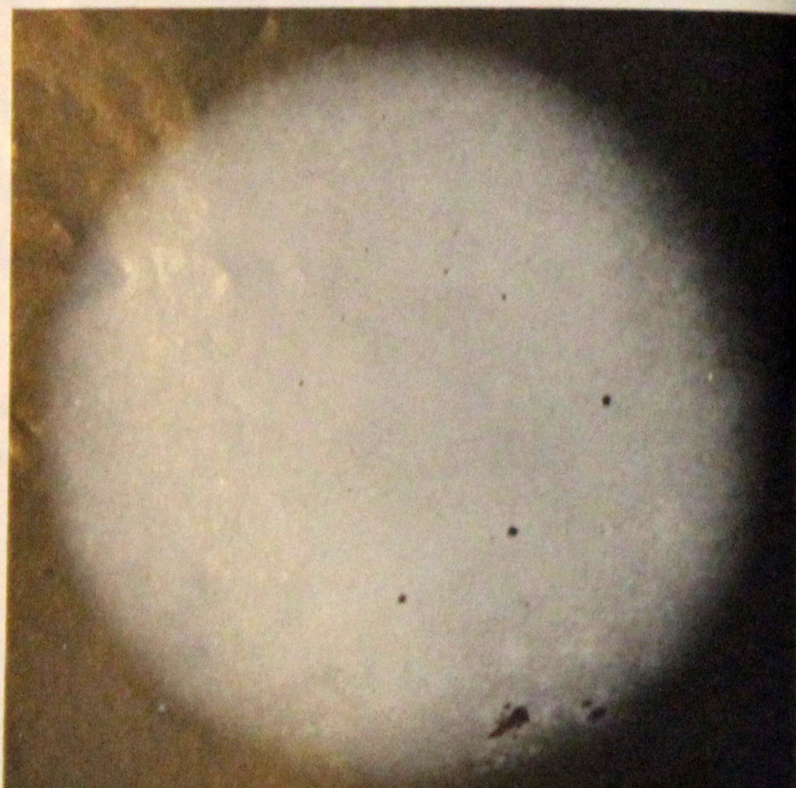
Getting details of the structure of the sun isn't easy, either. This, taken at the Sacramento Peak Observatory, through an H-alpha birefringent filter passing a band only 0.65 angstroms wide, shows an active area of the sun on a large scale. The blurring of poor resolution is obvious—and due to Earth's atmosphere, not poor camera quality.

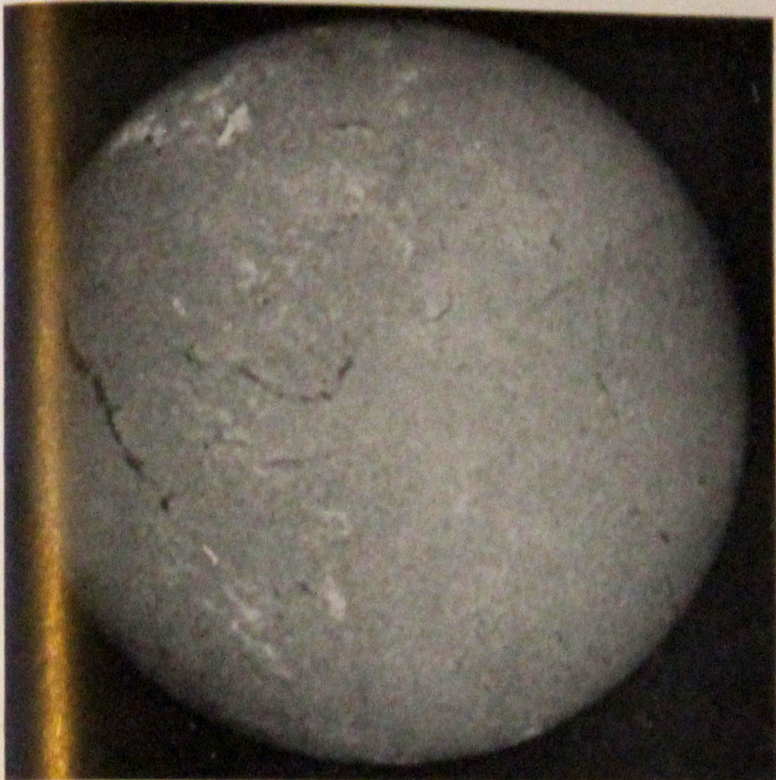
sion on its face looks over and admits that the picture isn't silent at all. It's ear splitting. Shrieks and booms, growls and rumbles, cracks and hums—any sound which words have been found for and virtually everything for which they haven't. The imagination wants to go off to watch a rocket launching as a relief—or possibly to hide his embarrassment—on the grounds that rocket noises couldn't possibly match this racket. Even the nuclear explosion in the memory record would go unnoticed in this bellowing hell. Actually, the sudden bang of an explosion is about the only thing missing here—no, we have even that; the planet-splitting crack of a gigantic mass of gas accelerating upward from somewhere below the photosphere until it reaches a speed supersonic both for itself and the surrounding gas. After all, that's just what happens in a dynamite explosion; why should the sound be different? The sun does seem to have good imitation explosions; but the imagination remarks with a slight sneer that you could hardly expect the real thing in that environment. Convection-driven—that is, gravity-driven—phenomena just aren't sudden enough to qualify. He never seems to learn, that imagination—

But he learns quickly enough. We've already gotten used to the sudden brightening of a hydrogen flocculus—one of the clouds of gas hanging almost motionless a few thousand miles above the photosphere, looking like dark blobs against the brilliant "surface" when seen from above—and this particular brightening doesn't attract our attention at first. If we notice it at all, we dismiss it with the thought that the thing will fade again shortly. Well, it does; but first, it *does* attract attention.

It gets brighter and brighter and hotter and hotter—in every sense. We need more than just our optical instruments back on Earth, now; light alone isn't going to tell the whole story. There *is* light, sure; all sorts, from soft X rays to the longest radio bands we can receive. There is also sound, and the imagination winces. Here, at last, is the really big bang. Or can it be called a bang, which implies relatively brief duration? This one doesn't stop. Each second seems as though it must represent the peak, but each second the sound grows louder. Atoms hurtle frantically against each other, showering electrons abroad and claiming others with a vicious spit of radiation. Electrons traveling too fast to be caught are accelerated as they pass near stripped nuclei and radiate unpredictably themselves. Nuclei driven at speeds

These three shots (pp. 94, 95 & 96) were taken almost simultaneously on March 13, 1959—but by three very different techniques. Photograph on Page 94 was taken in ordinary white light, at the United States Naval Observatory, in Washington, D.C. The one on Page 95 is from the United States Naval Research Laboratory, also Washington, D.C., using the birefringent filter centered on the H-alpha line. However, the picture on Page 96 was taken from an Aerobee-Hi rocket, using a special camera developed by the Navy, and also using a filter, centered on the Lyman-alpha line of Hydrogen.





half that of light hurtle out of the region still ionized.(13) The flocculus, now an expanding, rising bubble of gas blazing even by solar standards drives upward at perhaps four hundred miles a second. The work of expansion, work done against the local force fields, and the emission of radiation all strive to rob the mass of energy; but it is many minutes before the effects of the losses can be noticed. Eventually they can, and the mass cools; one to three quarters of an hour after the start of the phenomenon, there remains a not every unusual prominence, as far as the sun is concerned. In that time, the flare has disposed of enough energy to put the top half mile of North America into orbit. (17,19,25,26,30)

On Earth, things are still happening. The light, of course, reached our instruments a little over eight minutes after it was emitted. The noise,

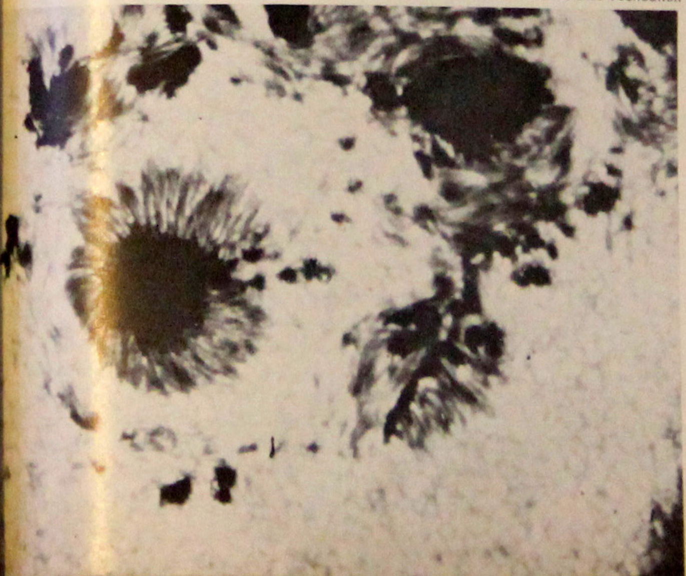
thanks to the nature of the transmitting medium, is mostly refracted into the body of the sun; what little is actually broadcast gets to us very late and too feeble to detect. (Yes, I did say *very late,* rather than *not at all.* The earth is technically inside the sun's corona, which is not a perfect vacuum and *will* transmit shock waves).

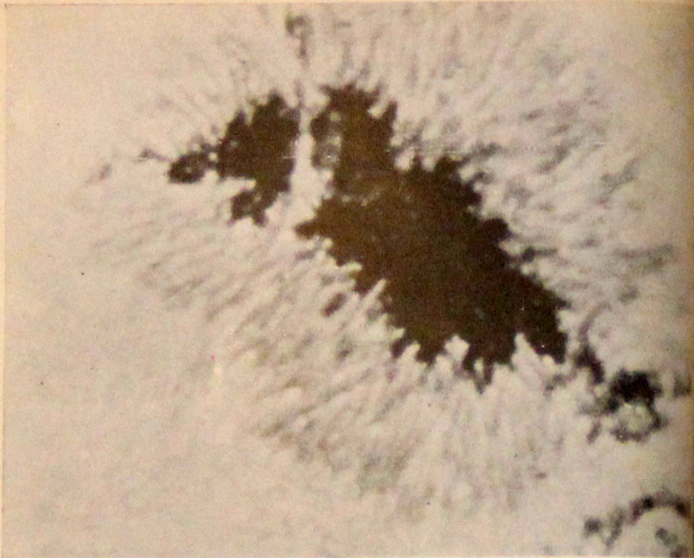
Particles also reach us. A few minutes after the first of the light makes itself noticed, particle counters on the sunward side of the earth start clucking. Strictly speaking, they have never been entirely silent, since there's a fairly steady background of cosmic "radiation" which isn't particularly affected by little things like solar explosions; but now the counters, and the men keeping track of them, really start to sit up and take notice.

Actually, the counters aren't registering particles straight from the sun —at least, the ground-mounted ones aren't. What the equipment in orbit does I'd very much like to know. What are actually recorded are showers of nuclear fragments produced in the upper atmosphere by collisions between the nuclei of atmospheric atoms and ultra-high-speed, ultra-high-energy nuclei which may either have come from the flare directly or, more likely, have been produced in another collision a split second earlier. What finally reaches the surface may be the fifth or tenth or fiftieth generation descendants of the original particle (fiftieth doesn't seem likely; target shooting conditions are pretty bad), forming a shower which may spread over acres. (6)

Rockets can get out into space . . . but United States rockets can't, as yet, carry the massive equipment needed for precision photography. Balloons can carry the essential equipment to 80,000 feet—and did, on August 17, 1959. This active sunspot group produced a major magnetic storm on Earth the day before the flight, causing major disturbances to radio communications, and a brilliant auroral display. The photographs obtained by the balloon-borne telescope revealed never-before detected detail.

National Science Foundation





National Science Foundation

White dots in center of sunspot are shown clearly for the first time in this photograph taken 80,000 feet above the earth in STRATOSCOPE I balloon-borne telescope. Less than 200 miles in diameter, these spots are apparently convection cells of rising gases, hotter than the surrounding area, but strongly suppressed by the magnetic field of the sunspot. The long diameter of the black area is roughly the diameter of the earth.

Even so, it is possible to measure pretty closely the direction from which the original particle came, especially if quite a lot of its descendants are spotted; and there seems little doubt on the basis of direction and time that the flare was the original source. As the minutes go by, the particles keep on arriving, but with gradually decreasing energy. The imagination notes this, and nods his head happily. Obviously most of the particles started at the same time—the time of the flare—from the sun, and quite naturally the ones with the hardest kick reached us first. Situation well in hand. The things will probably keep coming for hours.

They do, but long before the flare is over the imagination is less smug.

In fact, it's tearing its hair. Within a very few minutes, in fact, the nice definite direction readings which said that the flare was the source of the particles—or at least, that the sun was; there's a limit to the precision of this cosmic-ray-direction business—are starting to scatter. North, south, east, west and all reasonable combinations of these directions—the source is *spreading*. Maybe these late, low energy arrivals are being scattered by the atmosphere? Qualitatively sound, but quantitatively inadequate—the stuff is starting to arrive on the night side of the planet. *One* particle might get around there after a series of collisions, even though each collision doesn't deflect it much; but three quarters of an hour after the flare starts, the night side of Earth is being "illuminated" by the things as thoroughly as the sunward side. Trying to blame that on the atmosphere is like dropping a double handful of turkey dressing into a Mixmaster and getting out half a loaf of bread and a thimbleful of spice—conceivable, but no one would put much money on it.

We can't assume that particles of non-solar origin are responsible, either; this flood started within a few minutes of the solar flare, and it's the best part of a day afterward before the number of arriving particles drops back to normal; and this is the usual story—if it were an isolated instance we could invoke coincidence, but that's out in this case.

Well, how about gravity? That accounts for celestial motions in general. It's a force that can certainly bend the path of a moving object; maybe that's what is swinging these nuclei around to Earth's night side. Unfortunately, that notion never gets off the ground, though; the slowest of the particles is traveling at many times the escape velocity of the sun, so that Earth's gravity would hardly put a kink in its path and even the sun's much greater pull can't possibly drag it back to collide with the spaceward side of our planet. Poor old lazy, conservative imagination! What's happening, anyway? Critics finding fault with your pictures, just because of a few blank spaces on the canvas?

It's been a rather conceited imagination, of course, anyway; one which felt that a couple of dozen pieces of a thousand-piece jigsaw puzzle were plenty for judging the nature of the picture. He could live in this happy dream world as long as his dozen pieces were all bits of leaves and branches, and he could feel sure the picture was a forest; now, however, someone has found some blue that might be either sky or water, and some yellow that may be desert sand or possibly part of a campfire, and at last the imagination has come in with his ears drooping. He wants a lot more pieces of the puzzle before he does any more picture painting; people are getting too critical of his fragmentary efforts. What's this bit of brown, boss—part of a hat, or is there a bear stealing something from beside the campfire—if it is a campfire—or is it maybe part of a tree trunk as I thought in the first place?

Less figuratively, if the particles received in the last eighteen hours all came from that flare, why didn't they all come from the direction of the sun, as Newton's laws seem to say they should? If the downward-moving material in the prominences is falling, why isn't it accelerating at twenty-seven gees? That's what gravity should do to it. Why, for that matter, does some of it not fall but just hang there? The gravity isn't *that* much weaker a few thousand miles above the photosphere. Why are the sunspots cooler and quieter than the rest of the "surface"? Why does a flare start emitting soft X rays, and gradually shift to longer and longer waves—sometimes quickly and sometimes much more slowly? (26) It's not just temperature change, since the flare isn't hottest at the beginning. Why do prominences which are raining down at a steady rate quite suddenly change to a different rate? (14) And why, above all, does a flocculus or quiescent prominence which has been hanging inoffensively above the photosphere making its presence known only by the hydrogenalpha light it was absorbing, so that it looked like a dark splotch against the sun, suddenly run from a temperature of perhaps thirty thousand degrees Kelvin to—what? A hundred thousand degrees? Eight hundred thousand? Two million? Just what do we mean by these temperatures, anyway? (8)

People have been known to snicker at Sir William Herschel's belief that sunspots were holes in a luminous cloud envelope through which we were viewing a darker, colder, perhaps habitable world; thermodynamics—which didn't exist as a scientific discipline in Herschel's time—tells us firmly that the inner part of the sun can't be generally cooler than the outer since energy is patently flowing from the inside out. That's all very well, but now astrophysicists speak calmly of photospheric temperatures of six thousand degrees, prominence temperatures around thirty thousand, and coronal temperatures running from eight hundred thousand in quiet regions up to four million or more in really disturbed ones. (8,9,11). Have the laws of thermodynamics been repealed?

No, not yet. It's perfectly possible, by doing the appropriate kind of work in the appropriate place, to pile heat energy up in one spot against the "normal" temperature gradient, or to pump it out of one spot and leave an energy vacuum. You probably own a refrigerator and are familiar with the latter trick, and you've certainly familiarized yourself with the former one by lighting a match.

In addition, it's perfectly possible to have some of the particles in a given mass of matter at a higher temperature than the rest—in fact it's inevitable, since we have come to regard temperature as a measure of the kinetic energy of the particles and you never have a mass of material with all its particles moving at exactly or even nearly the same speed.

We seem to have two alternatives.

then. Either the high temperatures we seem to find in prominence and corona simply represent the tiny fraction of their atoms which would be moving that fast anyway, strictly according to probability, or some unexplained work is being done.

My lazy imagination makes a dash for the first alternative and has to be beaten off with a horsewhip. It just isn't so. There could not possibly be enough atoms at a million degrees, according to the observed behavior of gas clouds, to affect our instruments this far from the sun in the way they are affected. Hot as the general mass of gas may be and is, only a tiny, tiny percentage of its atoms could be that much hotter; and that tiny percentage would not make itself known in the "noise" of their more conservative fellows. No, somehow, somewhere, work is being done.

For three centuries now whenever there was evidence of work being done in the cosmos, the astronomer has thought of gravity. Work involves force and distance; and what other force is there? What else is holding the planetary system and the star clusters and the galaxies together? What keeps us and the air we breathe and the water we sail over clinging to this mud speck we call the earth? And what, for that matter, makes it such a grim task for our rockets to get away from it? Celestial mechanics has been built on gravity; surely there's some way we can imagine for gravity to do the work which is being done here in the sun's atmosphere.

To a certain extent, there is. Parts of a few of the questions we have just asked can be explained by our old friend. A bubble of gas a little hotter than its surroundings, for example, will start rising because of gravity and if it rises into regions of lower and lower density it can reach supersonic speeds. That will set up shock waves whose compression effect can give us temperatures in the prominence category. (9)

If the convection bubble has, say, a millionth of the mass of the earth, and reaches a speed of eight or nine kilometers a second, it will have a kinetic energy comparable to that released in a solar flare; all we have to do is find a large, brick wall for the bubble to run into, and we can expect the energy to come out as heat. And right there, gravity has to move over. We can imagine a gravity field which would "brickwall" such a mass of gas near the surface of a white dwarf star, but most emphatically not anywhere near our own sun. I was tempted at this point to tell my imagination that his canvas was mostly blank instead of having just a few little gaps, but before I could get my mouth open he got his own blows in. Smeone must have told him that the best defense was an attack.

"All right!" he cut in. "I'll paint the rest of the canvas. Just get me the information. Let me know what forces are acting, and give me equations describing their behavior, and how much there is of everything, and I'll put da Vinci and Michelangelo in the shade. Just give me complete information and I'll have the universe on canvas, not just this dinky little star."

Sneaky character. After all, it's *his* business to tell *me* what forces *might* be acting, so I can look for them after he's helped me design apparatus for the search. When I put this to him, though, he came back with, "What have I been doing all your life? You've been doing experiments yourself, and reading about other people's. You're familiar with a lot of forces; I've told you about 'em already. Now get to work with those observations and let me relax for a little while!"

And he's right, darn him. Back to the—no, not the lab and observatory, but the old textbooks. As he says, I've heard about a lot of forces already; let's see if they can be made to do this work before we try to find any brand new ones.

There seem to be four principal candidates: nuclear force (which may be a whole family of forces); electricity; magnetism; and the gravity we've already discussed.

Nuclear forces are certainly sufficient, as far as sheer intensity goes. In fact, it's no news in these pages that they probably account for the prime driving force of any star. Unfortunately the conditions which seem necessary to make them available for outside labor seem to be met in the cores of stars, not in their atmospheres. (Exception: If you're wearing a luminous-dial watch, there are a number of fifty billion degree particles on your wrist—some intense local heating supplied by work done by nuclear forces). It is, of course, conceivable that nuclear reactions stimulated by unknown means actually occur on the spot to turn a dark flocculus into a flare, but there seems no evidence just now for such an assumption and a good deal to be said against it. What we seem to need is less a prime source in the atmosphere than methods of transporting energy from core to surface, methods for storing it in some form at or near the surface, and methods for converting that stored energy quickly into other forms when conditions are right. Nuclear forces don't seem to fill the bill.

Gravity, at the other end of the line, has been pretty well disposed of already, but deserves another word or two. It's the feeblest of the forces, if one can really make comparisons on a common basis. Electricity, magnetism, and gravity all seem to be described adequately by the inverse square law—that is, the force each exerts can be expressed algebraically by $F=kXY/r^2$. While the X and Y terms are not really comparable, being mass in one case, charge in another, and pole strength in the third, the "k" term for gravity as the equations are usually used is far and away smaller than the "k" for either of the others. In more concrete terms, two nickels a thousand miles apart will exert a gravitational pull on each other of about 7×10^{-23} dynes; but if the positive and negative electric charges in a single nickel were separated by the same distance they would attract each other with a force of about two thousand tons. (Those figures are rough, believe me; but a factor of something like 10^{32} is quite a difference even with a few slide rule errors.) Gravity, it should be plain, needs a lot of mass around before it can accomplish much; electricity doesn't.

The sun, of course, does have a tremendous amount of mass, but its gravity field is a nice, symmetrical, radially decreasing one except for very tiny percentage variations due to local differences in density in and around convection currents. If the equations we use to describe gravity are even roughly correct, its only contributions to solar phenomena are the core pressures which make nuclear reactions possible in the first place and the convection currents we've already mentioned.

Electric field, all things being equal, seem far more powerful at least potentially than gravitational ones. Like the latter, they are inverse square forces; unlike gravity, they come in two sorts. Ben Franklin noticed this, and decided that like sorts repelled each other and unlike sorts attracted, which was clever of him; but I wish he hadn't called the two sorts positive and negative. Have you ever tried to discuss electric fields with a batch of ninth graders who haven't really digested their first year of algebra? If only Ben had called them Red and Blue, or Pat and Mike . . .

But he didn't and we're stuck with plus and minus. That's really the principal fact about electric field interactions—Ben's rule mentioned above. Of course, we can find or set up a physical situation which will demand quite highbrow math for a numerical solution, but fundamentally kXY/r^2 tells the story. We've made some headway, though; we now have potentially a pushing force as well as a strictly pulling one.

The interaction of electric fields with magnetic ones, and of magnetic fields with each other, turns out to be a far more complex story, though. Perhaps this is why Hale, back in 1908, developed the healthy suspicion that to understand the sun and solar phenomena we would have to learn a lot about solar magnetic fields. He may also, of course, have been influenced by the decided resemblance —sometimes—of the solar corona to the typical high school diagram of the lines of force around a bar magnet. Whatever inspired him, he started a line of solar magnetic investigation which has continued both in astronomical observatories and physics laboratories down to the present

A picture has been building up here, from the combined efforts of a lot of investigators and their imaginations. It is a different picture in many ways from the relatively simple, glowing, tornado-riddled ball of gas which my own imagination has just scraped off the canvas. It still has many blank areas, and will have for a long time yet; but what shows already is certainly interesting. To see it all clearly, though, I had to do just what we said a little while ago; go back to my undergraduate days, dig out the old books, and bring my imagination with me. The lazy critter kicked about it, but he came, and neither of us regrets it.

Here's what we got—in words. Some day I may be able really to think and express myself in the far more terse and convenient language of higher math, but the day hasn't come yet.

Some of you have probably amused yourselves with a little gadget looking rather like a hockey puck which appears to have the laws of friction suspended at its lower surface. It skates merrily around a table top at the slightest push with no sign of wanting to slow down, until the little CO_2 bottle inside it runs out and the flow of gas from the central hole out over the lower surface stops. Perhaps you have tried to force the toy down into overall contact with the table by main strength; if so, you know what the word "slippery" really means. The slightest sideways push and off it goes. It's like trying to catch a drop of mercury.

A similar form of amusement in a high schol physics class is to get a couple of football players, arm each with a husky Alnico horseshoe magnet, match like poles on the magnets, and have the boys try to push them together. Once again, there is large resistance to compression but none to any sideward component. The boys keep skidding the poles out of line, and if they lose their tempers run some risk of bumping heads.

Seemingly, there is some analogy between a magnetic field and a mass of gas. Perhaps it is not a very close one; analogies can certainly be pushed too far—witness the effect of the Bohr solar-system atom on a generation of science fiction. One of my chemistry teachers enjoys pointing out that no analogy is perfect; if it were, it would be an identity instead. We'll keep our eyes open for weaknesses, then. One is obvious enough; if we turn one of the magnets over so that unlike poles match, they stick together. Comparing that attraction to a pair of Magdeburg hemispheres or even Bernouilli force would be straining things pretty badly.

Still, the analogy will have its uses. There is a force from a confined mass of gas, and from a magnetic field; both forces act over an area, so they furnish pressure; both forces can operate through a distance, so they can do work—one thing we need desperately to solve our solar problems. Both, therefore, involve *energy*.

Fundamental differences seem to lie in the fact that the gas pressure is nondirectional—it makes no difference where we bore a hole in a tank of compressed air; out it comes anyway—and will act on any matter whatever. Magnetism is highly directional and is very choosy about the sort of thing it pushes or pulls. In general, it is interested only in another magnetic field. Its action on an electric charge is explainable on the basis of the magnetic field the charge itself possesses, and its action on matter is a function of the latter's electronic structure and therefore its charge and magnetism. (4,5)

If we want to make sensible comparisons or even paint halfway realistic pictures of either gas cloud or magnetic field, we must be quantitative. How much energy is in field or cloud? Find or invent a formula—stop sniggering, Imagination—on the basis of reason or experiment or both. Which way does the force act? Find out by experiment, and express it with vectors. Words actually aren't enough, as we've already admitted, but they help; words like "volume" and "molecule" and "line of force." We can't help using these words in discussing this subject. The first two we probably understand fairly well—at least, hearing them probably flashes similar pictures in your mind and in mine; but just what is a line of force?

To most of us it's probably a pattern of iron filings formed on a piece of paper lying over a magnet—the thing our high school science teacher showed us some years back. To the mathematical physicist it's a symbolic convenience with little or no concrete picture behind it. Maxwell likened some of the properties of magnetism to a flow, but he made no attempt to explain what was flowing and certainly knew that it wasn't a very good analogy. When he talked about magnetic "flux" as being expressed by so many lines of force per unit area he certainly didn't mean to imply that there was magnetism-free space between the lines, though I've read science fiction stories whose authors seemed to think so. It must be those iron filings.

Whatever Maxwell and Faraday thought, they certainly regarded the lines simply as useful fiction. One could describe the behavior of magnetic fields by saying that the lines of force tend to shorten like stretched rubber bands, that they tend to repel each other, and that each line is a closed loop. The last fact is simply another way of saying that the line of force is so drawn that its tangent at any point gives the direction of the magnetic force vector at that point, and that magnetic fields as far as is known contain no discontinuities. There are lines going through *every* point in the field, even though the number of lines, by convention, is finite. Of course around the magnets our football players were using the field volume was so small that we could consider the lines packed in contact anyway (or at least, a certain sloppy imagination of my acquaintance could); but in the space between planets, and still more in the vaster spaces between the stars and galaxies, the temptation to spread the lines out and think of real gaps between them might get a little too strong.

I didn't say *empty* space, of course. We all know better than that. There's too much matter in space to call it empty, and too much of that matter is electrically charged for a magnetic field to treat it as empty. That is really why magnetic fields have become so interesting to astronomers.

While uncharged matter may be affected somewhat by magnetism, the real, prime problem is the interaction between magnetic fields and the charged gas clouds of varying densities which make up the stars, the cosmic rays, the aurora, the interstellar nebulae, and the solar wind that Isaac Asimov described here a few months ago. Just what do magnetic fields and plasmas—charged gas clouds—do to each other?

We have some laboratory evidence, and even some everyday experience, on that. Our plasma may be a group of hydrogen ions in a cyclotron or a group of relatively free electrons in the metal windings of an electric motor. In either case when the charged particles are forced to travel across lines of magnetic force they experience a sidewise kick—a thrust at right angles both to the lines of force and to the direction of motion of the particles. In the first case, the ions take up a spiraling motion in the field, since the push changes direction just as rapidly as the particles do; in the second, the electrons are confined to the limits of the wire and the force on them is transferred to the wire and thence to the armature, which obediently spins (remember that!).

These experiments, though, involve too many solids. What happens if the whole system is gas? Things might be a bit different. For one thing, how do we get electric currents in the spaces between stars? And with no electric currents how can we produce magnetic fields?

We've given away the answer to that one, of course. Space isn't empty. Ten atoms, even a thousand atoms, to the cubic centimeter may be a better vacuum than man has made yet; but if any significant fraction of those atoms are ionized then charge can travel. If a charge travels, there is an electric current and a magnetic field. There's no law requiring the charge to be wrapped in metal. There's no problem in ionizing atoms in space, either, particularly near stars. There are plenty of high energy quanta ready to blast electrons out of their snug potential wells even between galaxies, and once the electrons are loose they don't get back in a hurry at those densities. Inside a star the densities are higher but the supply of quanta is larger too, so we still have ions and electric currents. Conductivity is far better here because of the high ion concentration. The plasma is moving—we've already seen that, in the sun. There *have* to be magnetic fields.

Which may not leave us much better off, if we don't check the statement more directly. Once upon a time there had to be an edge to the world, and not too long ago whatever went up had to come down again. Merely saying what we said about leaves us with two crying needs—to observe directly those fields which "have to be" there, and to find a quantitative, checkable means of describing and predicting them and their behavior.

The latter can be accomplished in the laboratory, if you don't mind doing your experiments on a small scale and extrapolating. Getting direct observational evidence is another story; so far our ability to explore space directly with magnetometers is sharply limited. Astronomers are used to this situation, of course. About all we've ever had to work with is light. We're a bunch of photon pinchers, putting every bit of radiation we can intercept through boot, thumbscrews and rack—pardon me, spectrograph, polarimeter, bolometer, interferometer, and whatever else our imaginations could dream up—in the effort to wring information from it. Then we plaster the poor thing up in a photographic emulsion and file it away until we can think of some new torture. But will all this technique, which was developed for photons, help us much in chasing down invisible magnetic fields?

The discipline will, anyway. Photons may not be of too much use here, but as we'll see they're far from being completely useless; and there *are* other things which reach us from outside. They arrive after being shaken, twisted, speeded up, slowed down, deflected, and generally mishandled by the very fields we want to study, because they are charged particles; it would be strange if a good collection of Imaginations couldn't get some understanding of the forces from their effects—soft soap, you'll notice.

These things which may, and as it turns out do, help so much are the *cosmic rays,* those viciously energetic arrivals from beyond which were so badly misunderstood for so long. There is still a chart on the wall in one of my classrooms which describes them as part of the electromagnetic spectrum with "wave length much shorter than gamma rays." That description isn't entirely wrong, at that; they do have a wave length. We know now that they are atomic nuclei, some of them at least coming from solar flares—particles down in that strange, foggy land of physics where the distinction between wave and particle grows hazy. They have a wave length, and it is certainly short by gamma ray standards, for wave length is inversely proportional to energy and some cosmic rays arrive with energies of ten billion billion—ten to the nineteenth power—electron volts. That, packed into a single atom, is energy of motion which my six- and seven-year-old sons would have some trouble pushing into a thrown baseball. If our bodies could really stop such a particle, we'd feel it—would even be hurt by it.

Fortunately, we couldn't stop it; it would either sail through us unaffected or would strike a single atomic nucleus in our tissues, shattering it into fragments which would go on without our noticing them, carrying most of the original energy with them. That's what happens in the upper atmosphere. The new fragments collide with nuclei in their turn, and those with others, and what we finally detect on Earth is a shower of remote descendants of the original particle, as we've already seen. If we have instruments scattered thickly enough over a large enough area of countryside to give us a fair sampling, we detect the suicide of the original cosmic ray by the practically simultaneous response of most or all of them. The number and energy of the responses and the area they cover gives us a reasonable estimate of the energy of the original particle.

Of course, particles of the ten billion bev variety aren't too frequent. If they were, we'd have a warm environment. Since temperature is average energy per particle it is perfectly reasonable to measure temperature in electron volts. In the room where I'm typing this article the temperature is about a fortieth of an electron volt per air molecule; there can't be a very large percentage of the whoppers described above. There are plenty of less violent ones coming in all the time, though, and the cosmic-ray flux is one of our sources of information about the magnetic fields in the space around our planet.

It's a little embarrassing to have to admit that it's almost the only source, too, as far as interplanetary space is concerned. Some of our satellites have carried magnetometric gear, but they haven't swept out a very large volume of space so far. Most of the rest of our magnetic information concerns the sun itself; and here our habits of photon pinching become useful once more. The spectroscope and some of its descendants have given us most of this information. (1, 9, 10, 15, 18, 21, 23)

Some of the information came from the ragged edge of the sensitivity limits of the early instruments, and the old, simple picture of the solar magnetic field is another one that Imagination has had to scrape almost to the canvas. This consisted of a fairly uniform field rather similar to the earth's and about twice as strong —say, a little over a gauss—detectable as might be expected principally in high latitudes. There were local irregularities; a suspicion of higher strength around the rice grains and definite, powerful concentrations around sunspots and sometimes areas not marked by spots. These sometimes ran up to several thousand gauss. The main field was directed oppositely to that of the earth; that is, the pole near the sun's north pole of rotation was a north magnetic pole. The spots were usually bipolar, with the leading spot "north" in one hemisphere and "south" in the other. This latter situation reversed with each roughly eleven-year half cycle of sunspot activity.

In the last few years instrument sensitivity has improved enormously. We can now make magnetic maps of the sun in a few minutes practically automatically, rather than by laboriously plotting the results of scores or hundreds of individual measures on different parts of the solar disk. The result is a much more nearly continuous, and incomparably more accurate and complete, coverage of solar magnetic phenomena. The changes in our picture are mostly, as might be expected, in the weak parts of the solar field; the sunspot story remains about the same. (10)

It seems that the general field of the sun is weaker than was supposed. It is also less uniform. Concentrations running up to twenty gauss or so seem to be associated with faculae; much stronger ones, as noted, with sunspots. Both of these are bipolar fields—every north pole has a fairly close south one. Each such region seems to undergo a regular cycle of development, starting small and weak, expanding and intensifying for a time, then expanding further but growing weaker and finally dying out.

In addition, there are rare but definite unipolar regions, areas where a north or south pole can be detected without its normal opposite number in the neighborhood. The presumption is that the emerging lines of force return to close their loops somewhere, but the area of return is so large that the field strength—"lines per square centimeter"—is too low to detect. So says my conservative imagination, anyway; maybe there really *are* magnetic discontinuities, though.

A similar phenomenon has occurred during the last few years with the general field. In 1957 the field in the southern hemisphere of the sun reversed polarity, while that in the northern hemisphere did not. The general field appeared for a while to have two north poles—admittedly very weak ones. The northern field didn't get around to reversing until late in 1958. The imagination when asked to picture the detailed solar field between those two times simply sneered. "It was a time of sunspot maximum," he pointed out, "and with all those strong fields in the equatorial regions why worry about a few lines of force from the poles. Maybe each south sunspot pole was a trifle stronger than its partner, or maybe one or two of them took on the whole job." He wouldn't say any more, and I still can't see clearly a picture of any individual solar magnetic force line for January, 1958. However, until instruments get sensitive enough to prove me wrong, I'll still believe that every line of force which leaves the sun gets back to it somewhere and closes its loop inside.

So much for direct observation. We do have in the sun some well observed fields not only complex at any given time but tending to undergo complex and sometimes quite rapid changes. Can we duplicate this situation in the laboratory closely enough to justify the feeling that we really know what's going on?

Well, it's easy enough to change the direction of a line of force. That happens with each iron filing we drop into the field of our high school display magnet, though that's not very obvious. If we have a few larger bits of iron among the filings, though—or a single iron nail—it becomes obvious enough. If we put another magnet near the first one, it becomes even more so. Lines of force don't seem very rigid.

But they're not completely flexible, either. A small magnet in the field of a large one moves, if it's free to move; is turned until its own lines of force create the least possible disturbance of those belonging to its big brother—until, in fact, the two fields merge indistinguishably and a good many of the lines of force thread their way through both magnets. An entire field can be moved, too; the sun's and earth's fields travel with them, and our football players could play catch with their magnets if we asked them to. The fields would certainly go along with the magnets.

But will moving *gases* carry magnetic fields with them? The answer to that question is not exactly self-evident, but it's one we can check in the laboratory. When charged gases and magnetic fields occupy the same space, but have different motion, which wins? Or is there some complex interaction with nobody winning?

The answers to these questions lie in a relatively new discipline, or hybridization of disciplines, which has been named magnetohydrodynamics. Like geophysics and biochemistry it is an application of the techniques of one field of study to the problems of another; in this case perhaps the synthesis is more complete than in the others. Biochemistry is certainly chemistry applied to biological problems more than it is biology applied to chemical problems, but magnetohydrodynamics cannot so easily be described as electromagnetic equations applied to the gas laws or van der Waals equations applied to magnetic fields, or even as both with any degree of completeness. Like most disciplines which include the term "dynamics" in their title this one is highly quantitative and its laws are best expressed mathematically, often in nasty things like differential equations. It's possible to express some of its facts and conclusions in words, of course; it's also possible to tell an orchestra how to play "Tannhaüser" without using written music, but the task would not be worth the effort as long as there were people around who could read music. In scientific matters it has become very worth while to make the comparable attempt of explaining an inherently mathematical subject without the mathematics. That's what I'm doing here, and anyone who thinks I'm trying to cover my ignorance of the math in question is wrong. I'm admitting it.

Roughly, the experimental and theoretical results seem to agree on the following answer to the questions we asked a moment ago. The field and the charged cloud *do* interact. There is no simple situation in which one stays put and the other gets pushed around, though we can sometimes approximate one. Each offers some resistance to being moved; each exerts a displacing force on the other—which in turn reacts on itself.

For the gas—or for that matter a liquid or a solid—the resistance is of course its inertia. (Doesn't it feel nice to have a familiar name for something, even if we don't know what it is?). The gas' ability to impart energy to something else depends on its own energy density—

that is, the "concentration" both of thermal energy, which is the random kinetic energy of the particles composing it and whose concentration can be called temperature, and of the overall energy of motion. That is, if a meteor or gas cloud is traveling at five hundred kilometers per second with respect to a magnetic field and has a temperature of a thousand degrees Kelvin, both the temperature and the speed are relevant.

For the magnetic field, the equivalents of inertia and energy density are harder to picture in familiar terms, which may not mean that we know any less about them. They depend on field intensity, which seems reasonable, but not in a simple way; the energy density of a magnetic field—the measure of the work which can theoretically be accomplished by destroying the field—is proportional to the *square* of the concentration of the lines of force per unit area. That may not be too startling; kinetic energy, after all, is proportional to the square of the velocity for matter.

The field and the plasma can do work on each other—can transfer energy, in other words—when the relative motion is at right angles to the lines of force. This we already know from our high school toy motors. The energy transfer involves a displacement of charge in the plasma; in other words, an electric current is set up at the expense of the kinetic energy of the cloud, of the magnetic field, or of both. If the matter involved can't conduct an electric current, it will accept no energy from the magnetic field. That's old hat to science-fiction lovers; the magnetic shields of spaceships have always been admitted to be useless against stone meteors. Theoretically, a substance of perfect conductivity would absorb all the energy from a field which tried to cross it, and would therefore be a perfect shield against magnetic force (Also the perfect shield against any electromagnetic radiation).

Even conductors which are merely "good" can take a good deal of energy in interacting with a field. Our electric generators make use of this fact, and it has shown up in other surroundings. In attempts to set up very intense magnetic fields during research projects, one technique has involved single-turn coils. These are essentially sections of thick-walled conducting pipe with a slot down one side. Electric potential applied at one edge of the slot runs a current around the wall of the pipe to the other edge. If a good, healthy jolt is applied, as by unloading a roomful or two of condensers, a very intense, though very brief, magnetic field is established. In the ten microseconds or so that a million-gauss field lasts in such a system, funny things can happen to the "coil." The field is trying to expand through the conducting metal, and naturally tends to induce a current in the process; by Lenz' Law, the current in turn sets up a field which tends to oppose the one generating the current. The two fields exert pressure on each other which in effect is a pressure on the inside of the pipe. (I told you to remember that motor.) The pressure depends on the magnetic field energy, which depends on the square of the field intensity, as we said. At a million gauss, the pressure far exceeds the mechanical strength of the pipe, and the latter survives at all only because of its inertia. Ten microseconds just isn't long enough to destroy a chunk of metal that big even with as much energy as the field has. However, the inside dimensions of the pipe may increase noticeably, and there may be some melting of the inner surface as some of the energy shows up as random particle motion—heat. A way out of this might be to use a poor conductor for the pipe; but then the capacitor bank couldn't send such a big current through it and the field wouldn't reach the desired intensity. It's the good old vicious circle which researchers spend so much time and imagination breaking out of. (7)

Ionized gases, of course, will offer far less inertial resistance to magnetic pressure than will solids, since as a rule they are far less dense. In general, in this battle between gas and field to control the motion of both, the energy densities of the two are the deciding factor. If they differ greatly, it may be possible to treat the stronger one as the "immovable object" for approximate solutions to problems. If they are equal or nearly so, the full complexity of the magnetohydrodynamic equations of state comes into play and the problem may not be solvable by current mathematical techniques.

There are some steady-state solutions, as it happens; situations where the various forces are in equilibrium and a physical picture is fairly easy to see. Some of the solar picture, happily, fits into one or another of these; much of it, inevitably, does not. Some of the picture outside the sun, and possibly some well inside it, fits the "approximate" situation where one factor overwhelms the other. Let's get back to the picture, and start Imagination swinging his brush again. He's been letting Memory do the work long enough.

It turns out that in and for some thousands of miles above the photosphere the concentration of ions, and hence the conductivity, are high. So, to put it mildly, is the thermal energy of the gas; and so, at least in "active" regions, is the magnetic field intensity. No approximations here. The energies involved are high enough so that gas and field are pretty thoroughly glued together. Where one goes, at least in directions at right angles to the line of force, there goes the other—of course the gas can travel *along* the lines of force easily enough. Just which is the prime mover in a given case is apt to be a hen-and-egg problem. Like the hen-and-egg problem the answer may well lie in some form of evolution, of energy forms rather than life.

In the outer corona, at the distance of the earth, the situation has changed. With the most favorable assumptions, the magnetic field strength can hardly exceed a ten millionth of what it was near the sunspot, with its energy density down by the square of that factor. The gas has lost some density, but not so much as the field; it's down to, say, a hundred atoms per cubic centimeter against something like thirty million in the inner corona. Unless the temperature has dropped by a factor comparable to that of the field strength, then, the gas is going to hold the whip; and the temperature *hasn't* dropped.

Sure, the black body temperature—the radiation equilibrium temperature of the hypothetical perfect radiator—at the earth's distance from the sun is only about a twentieth of what it is at the photosphere; but who said this gas was in radiational equilibrium? It isn't. Gases at a density of a hundred atoms per cubic centimeter don't radiate as black bodies; they're not enthusiastic about radiating at all. Furthermore, this gas is the solar wind, with an outward velocity of around five hundred kilometers a second; how about that kinetic energy? No, we still have to credit this stuff with a temperature of several thousand degrees, if we're trying to estimate its energy density relative to that of the magnetic field. In that case, the gas is the dominant partner by a factor of something like a million. The sun's field isn't going to deflect the wind to any extent. On the contrary, the solar wind is blowing the lines of force radially outward until an honest diagram of them might be mistaken for a picture of the sun's *gravitational* force lines.

That doesn't go on forever, of course. We're still pretty sure that somehow, somewhere beyond the earth's orbit, perhaps after going through all sorts of hard-to-imagine twists and loops as the solar wind finally breaks up into eddies, the lines maintain their reputation for endlessness, sneak back across the sun's equatorial plane, straighten out as they head into the wind again, and finally dive back into the energy source where they were born. Can we check on this? Yes, rather shakily. (6)

A while ago we mentioned that cosmic rays, which are charged particles which have run the gantlet of whatever magnetic fields there might be out there, might carry some information about their vicissitudes down to us. We can observe for a particular cosmic ray its direction, its energy, and its mass—that is, we can identify the type of nucleus on the atomic weight scale. (Correction: we can't get all this information about the *same particle* as a rule, but if there are enough particles we're all right.) Generally, the things turn out to be protons; most of the ones that aren't are alpha rays—helium nuclei. About one per cent of the total are heavier species, running about up to iron. This fits reasonably well with the universe's population of atoms, we think.

But devoting our attention to the first two factors, speed and direction, what can we learn? Let's remember our solar flare—the one we watched with our imaginations a while ago. The one that released the energy of about ten trillion Hiroshima type fission bombs.

This is about equal to the total energy output of the sun's surface in two fifths of a second. Admittedly, it took the flare over two thousand seconds to unload all this energy; something like ten thousand times as long in something like a ten thousandth of the radiating area. The flare was practically a second sun. More interesting, that load of energy was more than exists as heat at any one time in the entire region outside the photosphere—chromosphere and corona combined; and in any case, there's not the slightest evidence that either chromosphere or corona were being drained of heat to feed the flare. However:

Ten to the thirty-third power ergs is *not* more energy than can exist in (a) a volume of magnetic field of the size and intensity normally found in sunspot regions, or (b) as was mentioned earlier, the kinetic energy of a quantity of gas a millionth the mass of the earth traveling at less than ten kilometers per second. If we could dream up a mechanism which would cause the sudden collapse of such a magnetic field, we might have our flare problem solved; but perhaps we don't even need to do that. Remember our need for a brick wall in front of that rising convection bubble? Imagination is positively rubbing his hands with glee; because that bubble must be largely ionized. It's no trouble at all for him to dream up an arch of magnetic force lines connecting the two poles of a sunspot or other active area, and part of that arch just has to be horizontal. The field has energy comparable to the bubble; and there is the brick wall. The gas slams into the arch—possibly even guided into it by the more vertical parts of the field—and is abruptly decelerated and compressed. The field is stretched upward like a spider web under the impact of a bumblebee; and the imagination winces again. One forty-kiloton bomb was loud enough; a trillion hydrogen bombs are in a different league.

Of course, there's a catch or two. A flare, according to this picture, ought to be slowing down as we watch it; but things don't always work that way. In at least one case, a knot of material some twenty thousand miles in diameter speeded up in its outward flight from about sixty to about seven hundred miles a second within two minutes. (17) Even though this represents some sort of record performance, abrupt accelerations do occur quite often. If we are to make this general idea work, we'll have to assume a few complications. Maybe the original bubble or cell is complex in structure—not at all unlikely—or maybe some of the energy cycles back and forth between magnetic and kinetic. Maybe we'd better go partly or entirely to the other idea—that the field itself collapses partly or entirely and contributes its own energy to the phenomenon. All these possibilities are harder to check, since they do *not* represent steady-state solutions of the magnetohydrodynamic equations of state.

One such solution does help a little, though. It gives a picture of the arches we have just hypothesized, with a slight sag at the top; and resting in the sag like a sailor in a hammock is a great mass of ionized gas —a "quiescent" prominence or flocculus. We can at least "set up" mathematically for the impact we'd like. The inertia of this flocculus would contribute to the brick wall effect.

Things are encouraging so far. There seems at least reasonable chance of tying observed phenomena in with theory. Maybe if we check observations in other directions our luck will continue. Let's try the cosmic rays, since the optical observations were propitious.

About ten minutes after the flare started—or rather, was observed to start—high energy particles began to be detected on the earth. During the next ten minutes or so, when the visible aspect of the flare had reached its peak and was already subsiding, particles of gradually smaller energies continued to arrive from the general direction of the sun.

As time went on, though, the arrival directions began to scatter more and more widely; and by three quarters of an hour after the onset of the flare, when it was about over as far as optical observation was concerned, protons were arriving just about equally from all parts of the sky. It took fifteen or twenty hours for the cosmic ray count to drop back to normal, and during nearly all of this time there was not the slightest evidence that the particles were coming from the sun—or any other specific source.

It *seems* as though the first particles ripped their way to us without being bothered by any fields on the way. With energies—velocities, remember—able to get them here in less than twenty minutes that's not too startling. The next, slightly less energetic arrivals could have been scattered by the strong magnetic fields close to the sun, giving a "foggier image" of their source. Then, finally, material of widely varying energies came from all directions, like light to the eyes of a mosquito inside a frosted glass lampshade. It does indeed look as though the flying protons had tangled with randomly oriented, twisted magnetic fields somewhere beyond the earth, had been deflected in all possible directions including the ones toward our instruments, and had gradually filtered on into extra-solar space over a period of a dozen or two hours.

Other pictures are always possible, of course; of fields concentrated near sun and again near earth with little or no magnetism in between; or fairly concentrated radial tongues of field instead of the general, low-density radial distribution; or even extra-large, low density arches similar to those we've pictured over sunspot extending far out into the solar system. At the moment, the one we've pictured seems most nearly right, but one flare isn't much to generalize from.

Of course, there have been a good many flares observed; they are far from rare, though the really impressive "class 3" exhibits aren't too frequent. The general picture secured from these agrees with the one we've just painted, but details vary from flare to flare.

The highest energies among the flare particles seem to be in the ten to one hundred billion electron volt range; the really hot end of the cosmic ray spectrum apparently originates elsewhere. At the moment, it seems unlikely that it originates inside the solar system at all; but of course, there are magnetic fields outside the solar system, too.

So far, Imagination's picture has extended from just below the photosphere of the sun to some unknown but probably not very great distance beyond the earth's orbit, with a casual admission that things went on farther outside, and lip service to the fact that the whole business really originates farther *in*side. The time seems to have come to make our tame artist dig a bit deeper.

For that he needs mathematical tools, since there is no direct observational help. That's all right; he's been down there before with the gas laws to help. That time he came back with the now familiar picture of a gas sphere steadily increasing in temperature, pressure, and density toward the center, finally reaching conditions where hydrogen fusion could go on at a rate sufficient to maintain the observed energy output. He didn't pay any attention to such details as magnetism on that trip, but that's all right. He can take the same canvas with him and just add details. Maybe.

For this trip the mathematical equipment will have to be the magnetohydrodynamic equations of state, and we can hope some of the steady state conditions apply—after all, the sun isn't *too* variable a star. There's a chance.

And, it turns out, quite a good one. We don't have the whole story yet, because he's still down there digging; but an interim sketch he's sent back is very hopeful.

It shows a pair of torus-shaped magnetic fields circling the sun below the photosphere, rather like a pair of bicycle tires, one in each hemisphere, parallel—more or less—to the equator. One is directed eastward and one westward around the star. Convection currents tend, of course, to cut across these fields; and as we've seen, this can not only slow down the currents but move the fields. At times, loops of the field are actually carried up through the photosphere, forming the arches whose existence we've already suspected; the arches, as we've seen, may be squashed a bit by charged material settling on top, and thus form pockets to hold up some types of prominence.

The supersonic convection bubbles which heat the prominences seem to fit this picture; and such a bubble rising in a region where the toroidal field has already been lifted above the photosphere could get more than the usual supply of kinetic energy before finally encountering the field. This point, of course, is *not* a steady state and the mathematical situation is more than a little shaky; but it looks reasonable. The imagination, which has finally learned some caution, is now calling this a "constructive daydream."

This seems a rather unsatisfactory and incomplete state to leave the picture in, but it's all that can be done for now. It's almost like current history, really. Someone who has been the indisputed top for a long time—undisputed among a certain group, anyway—suddenly finds that he's not alone. American technology in the mind of the average American suffered that blow when the first Sputnik went into orbit; now it's being suffered by the old master of celestial mechanics, gravity. Move over, brother. We know you, and you've been a pretty good boss, but the books aren't balancing any more and the work isn't getting done.

Even beyond the little bubble of space and time which is the Solar system of right now, the need for something besides gravity is being felt. All attempts to account for the spiral shape of some galaxies, including our own, by gravitational forces alone have proven unsatisfactory. Admittedly, no really good explanation in terms of magnetic fields has been forthcoming yet either; but there *are* magnetic fields of galactic scope. Quite a lot of the light scattered by interstellar dust is polarized in consistent fashion, indicating that the dust particles are oriented over distances of scores of light years; magnetic fields can do that and, offhand, nothing else we know of can.

Timewise, the old question of the origin of a planetary system remains in an unsatisfactory state. The dynamic encounter theories which had the planets torn from the sun in a near-collision of stars were pretty thoroughly disposed of in 1940 when Spitzer showed that if enough matter were torn out this way to form the planets it would have to involve such deep layers of the sun and therefore such high temperatures that it would explode rather than coalesce. This at least spared us the need to assume such an unlikely event as a star collision in the first place, but left us with the various accretion theories; the descendants of the old Kant-LaPlace nebular hypothesis. These have always suffered from an inability to account for the fact that about ninety-nine per cent of the Solar system's angular momentum resides in the planet Jupiter, while a corresponding fraction of the mass is in the sun. They also have been attacked on the grounds that rings of matter circling the sun should not coalesce into planets, either—not just on the grounds that Saturn's rings don't, but on perfectly good mathematical arguments involving gravity and energy.

Gravity was disappointing there; but fairly recently Dr. Harold Urey reconsidered the accretion problem from another viewpoint. He is a chemist, and included chemical—essentially, electrical—forces. It was all very well to show clearly that two particles colliding in space will either bounce apart or shatter rather than stick together; but it becomes hard to believe if either or both particles happen to be *wet*.

And as far as angular momentum goes, why can't a rotating star, whose magnetic field is presumably rotating with it, start pushing ions in its vicinity sideways? It makes no difference whether the ions or the field is moving; ions have trouble cutting magnetic lines of force in either case. Couldn't a star with a good deal of gas in its neighborhood start swinging that matter around it, slowing its own spin down in consequence? It would be nice to believe it, especially for science-fiction writers, who need extra solar systems in their business and would like to see them as something normal.

In that connection, it seems at the moment that most of the stars hotter than about F5 in the spectral sequence have high rates of spin, while the cooler ones in general do not. There seems no obvious reason why a mass of gas too small to form a big, hot star would automatically have less spin than its fellows; if anything, the reverse should be true—at least, my science-fiction oriented imagination immediately points out that the *less* rapidly spinning gas clouds ought to be the ones which can collect *large* amounts of mass without having centrifugal problems. There is a widespread suspicion among astronomers that most stars start out with comparable amounts of spin, but that the later-than-F5 types have transferred theirs to nearby objects—just maybe, planets. The only obvious hitch in the whole matter is that one would expect the *hotter* stars, which presumably have more ionized matter around them from that very fact, would have more stuff to transfer their spin to.

I don't claim that's an insuperable obstacle to accounting for planetary systems magnetically, but it certainly is evident that a few more details will have to be clarified before anyone can justifiably say he knows how planets are formed.

For that matter, we don't know that all stars have magnetic fields. Some certainly do—some much stronger ones than the sun; one has recently checked in with what appears to be a general field of some forty-five thousand gauss (28). We'll have to learn a bit more, though, before we start applying magnetics-based theories to stars in general.

We've made one big forward step, though, if only in our habits of thought. It may be scientific to try to reduce problems to only one variable at a time—in fact, it's about the only way to tell what is done by each variable. When we go back to actual problems, though, having learned about the separate factors, it behooves us to remember that there may be several factors acting at once. I won't insult the astronomical profession by saying that it had forgotten there were any forces but gravity; I know it hadn't. It is high time, though, that we made more use of what mathematical techniques there are for dealing with several variables at once. Electromagnetism and the gas laws have blended very nicely—now let's hybridize a few more fields of effort.

And let's, for goodness' sake, find some means of preventing students from being afraid of higher math. I'd like to be able to do some of those magnetohydrodynamic problems myself; and I very much doubt that I'll ever be able to. If you can find that method for overcoming algebrophobia, please use it on *me, now!*

References

References here come under three headings. In the first group are a number of relatively elementary texts which my imagination and I found we needed to bone up on fundamentals. Many others would have done; the ones we actually used were:

(1) "Astronomy," Robert H. Baker, 6th Ed., 1955, van Nostrand

(2) "Our Sun," Donald H. Menzel, Blakiston, 1950

(3) "Magnetism" article in *Encyclopedia Britannica,* vol. 14, p 673B ff. 1956 ed.

(4) "Electricity and Magnetism," Gilbert, MacMillan, 1941

(5) "Electricity and Magnetism," E. R. Peck, McGraw-Hill, 1953

The second group consists of articles of fairly recent vintage, dealing with solar phenomena in general and magnetic and magnetohydrodynamic items in particular. These were:

(6) "Science in Space," Chapter VII (Published separately), Physics of Fields and Energetic Particles in Space. National Academy of Sciences—National Research Council, 1960

(7) "High Magnetic Field Research," Harold P. Furth, *Science,* Vol. 132, 12 Aug. 1960, p. 387ff.

(8) "Hot Spots in the Atmosphere of the Sun," Harold Zirin, *Scientific American.* August 1958, p. 34ff.

(9) "Some Advances in Solar Research," Donald H. Menzel, *Sky and Telescope,* August 1957, p. 415ff.

(10) "The Magnetism of the Sun," Horace W. Babcock, *Scientific American,* February 1960, p. 52ff.

(11) "Fraunhofer Lines and Heights in the Sun's Atmosphere," Orren C. Moehler, *Sky and Telescope,* April 1960, p. 124ff.

(12) "Indirect Detection of Solar Flares," P. J. Del Vecchio, *Sky and Telescope*, August 1959, p. 546ff.

(13) "Fast-Moving Disturbances on the Sun," G. E. Moreton, *Sky and Telescope*, March 1961 p. 145ff.

(14) "The Fine Structure of Solar Prominences," Donald H. Menzel, *Sky and Telescope*, November 1960 p. 252 and December, 1960, p. 330ff.

The remaining items are brief news reports, sometimes well illustrated, from *Sky and Telescope*, which seemed to fit the picture.

(15) "Solar Magnetic Fields" October 1954 p. 423

(16) "Origin of Solar Flares" June 1955 p. 321

(17) "Great Solar Explosion" July 1956 p. 398

(18) "Changes in Sun's Magnetic Field" Sept. 1958 p. 555

(19) "Solar Flare of May 10, 1959" August 1959 p. 544

(20) "Solar Radio Bursts" August 1959 p. 556

(21) "Observing the Solar Magnetic Field" August 1959 p. 557

(22) "Project Stratoscope" December 1959 p. 79

(23) "General Magnetic Field of Sun" January 1960 p. 147

(24) "Radio Storm in Sun's Corona" January 1960 p. 147

(25) "Flare Patrol Photographs" January 1960 p. 147

(26) "Flares of July 16, 1959" April 1960 p. 339

(27) "X-ray Photo of Sun" September 1960 p. 143

(28) "Intense Magnetic Field" March 1961 p. 131

(29) "Local Doppler Effects in Photosphere" April 1961 p. 210

(30) "X-rays from Solar Flare" April 1961 p. 212

Some, but by no means all, of these news items were abstracts of longer papers which were not available to me.

THE END

THE ANALYTICAL LABORATORY

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PLACE	STORY	AUTHOR	POINTS
1.	Sense of Obligation (Pt. 1)	Harry Harrison	1.64
2.	The Blaze of Noon	Randall Garrett & Avram Davidson	2.76
3.	Fifty Per Cent Prophet	Darrel T. Langart	3.04
4.	Modus Vivendi	Walter Bupp	3.23
5.	They Also Serve	Donald E. Westlake	4.33

The Editor.