The Creation of Imaginary Worlds.

The World Builder's Handbook and Pocket Companion.

POUL ANDERSON.

This is an infinitely marvelous and beautiful universe which we are privileged to inhabit. Look inward to the molecules of life and the heart of the atom, or outward to moon, sun, planets, stars, the Orion Nebula where new suns and worlds are coming into being even as you watch, the Andromeda Nebula which is actually a whole sister galaxy: it is all the same cosmos, and every part of it is part of us. The elements of our flesh, blood, bones, and breath were forged out of hydrogen in stars long vanished. The gold in a wedding ring, the uranium burning behind many a triumphantly ordinary flick of an electric light switch, came out of those gigantic upheavals we call supernovas. It is thought that inertia itself, that most fundamental property of matter, would be meaningless--nonexistent--were there no stellar background to define space, time, and motion. Man is not an accident of chaos; nor is he the sum and only significance of creation. We belong here.

Once literature recognized this simple fact. Lightnings blazed around Lear; Ahab sailed an enormous ocean and Huck Finn went down a mighty river; McAndrew saw God in the machinery that man created according to the laws of the universe. But this is seldom true any longer. Barring a few, today's fashionable writers are concerned exclusively with Man, capitalized and isolated - who usually turns out to be a hypersensitive intellectual, capitalized and isolated among his own hang ups. This is not necessarily bad, but may it not be a little bit limited?

In science fiction, whatever its faults, we have a medium that still allows exploration of a wider, more varied field. Of course, the story with a highly detailed extraterrestrial background is by no means the sole kind of science fiction. It is not even in the majority. Nor should it be. Too much of any one theme would put the reader right back into the monotony from which he hoped to escape.

However, when a story does take its characters beyond Earth, he is entitled to more than what he so often gets. This is either a world exactly like our own except for having neither geography nor history, or else it is an unbelievable mishmash which merely shows us that still another writer couldn't be bothered to do his homework.

As an example of the latter category, John Campbell once cited the awful example of a planet circling a blue-white sun and possessing an atmosphere of hydrogen and fluorine. This is simply a chemical impossibility. Those two substances, under the impetus of that radiation, would unite promptly and explosively. Another case is that of a world that is nothing but sterile desert, devoid of plant life, yet has animals and air that men can breathe. Where does the food chain begin? What maintains an equilibrium of free oxygen?

At the very least, a well-thought-out setting goes far toward adding artistic verisimilitude to an otherwise bald and unconvincing narrative. By bringing in this detail and that, tightly linked, the writer makes his imaginary globe seem real. Furthermore, the details are interesting in their own right. They may reveal something of the possibilities in their own right. They may reveal something of the possibilities in these light-years that surround us, thereby awakening the much-desired sense of wonder. Finally, many of them will suggest important parts of the plot.

In the most highly developed cases, they practically become the story. Hal Clement's Mission of Gravity is a classic of this kind. But enchanting though it is, that sort of thing is reserved for writers who have the necessary scientific training.

What I wish to show here is that others can do likewise, in a more modest but nevertheless astonishingly thorough fashion. It doesn't take a degree in physics. It simply takes the basic knowledge of current scientific fact and theory which any person must have before he can properlywin this day and agewcall himself educated. In addition, it requires imagination and a willingness to work; but these are qualities that every writer worth his salt already possesses. Anyhow, "work" is the wrong word, if that suggests drudgery. The designing of a planet is fascinating--sheer fun.

Because it is, I believe most readers would also enjoy seeing a few of the principles Spelled out.

They involve mathematics, and equations are their natural form of expression. But too many people are unreasonably puzzled, even frightened, by equations. Those who aren't will already know the natural laws I refer to; or they can be trusted to look them up. So instead I shall offer a few graphs.* With their help, and just the tiniest bit of arithmetic, anyone should be able to start world-building on his own.

Needless to say, any serious effort of this kind demands more information than can possibly be squeezed into the present essay. Two reference books that are especially well suited to science fiction purposes and are, in addition, a joy to read are Intelligent Life in the Universe by I. S. Shklovskii and Carl Sagan (Holden Day, 1966) and Habitable Planets for Man by Stephen H. Dole (Elsevier, rev. ed., 1970). Of course, there are numerous other good works available.

Like every living science, astronomy today is in a state of continuous revolution. Any book is virtually certain to contain outdated material; and "facts" are always subject to change without notice. (Indeed, as I write, the whole set of methods by which the distances and thus the properties of other galaxies have been obtained is being called into question.) I have no desire to be dogmatic. If I sometimes appear that way in what follows, it is merely to save space. Take for granted that every statement bears a qualifier like: "This is my limited understanding of what the best contemporary thought on the subject seems to be."

Yet let us never forget that it is the best thought available. If we don't use it, we will have no basis whatsoever on which to reason.

Therefore, onward! Mainly we'll consider some of the possibilities regarding planets which, without being copies of Earth, are not as absolutely different from it as are the other members of our own solar system. Anything more exotic, h la Hal Clement, would take us too far afield. Besides, more often than not, a writer wants a world where his humans can survive without overly many artificial aids.

A number of parameters determine what such a globe will be like. They include the kind of sun and orbit it has, the size and mass, axial tilt and rotation, satellites--to name a few of the more obvious. Doubtless there are several more that science has thus far not identified. Our knowledge of these things is less than complete. But simply by varying those parameters we do know about, we can produce a huge variety of environments for stories to happen in. We can also gain, and give to our readers, some feeling for the subtlety and interrelatedness of nature and her laws.

Normally we begin by picking a star, real or imaginary. In earlier days, science fiction customarily put planets around the familiar ones like Sirius, Vega, Antares, or Mira. It was then legitimate enough, if a trifle repetitious. But today we know, or believe we know, that few of the naked-eye stars will serve.

Mostly they are giants, visible to us only because they are so brilliant that we can pick them out across immense gulfs of space. (Sol would no longer be discernible without instruments at a distance of about fifty-five light-years.) Now the red giants like Antares, the variables like Mira, are dying stars, well on their way to the dim, ultra-dense white-dwarf condition. If ever they had planets--their mass makes that unlikely, as we will see in a minute--the inner attendants have been seared or even consumed, as these suns expanded. If outer globes have been warmed up, this won't last long enough to do biological evolution any good.

Probably the majority of stars in the universe are still enjoying health. Their temperatures and luminosities vary enormously. The most important reason for this is the difference in their masses. The more massive a sun is, the more intensely compressed it becomes at its core, and thus the more fierce and rapid are the thermonuclear reactions that cause it to shine. This dependence of output on mass is a highly sensitive one, so that the latter covers a much smaller range than the former.

These stars form a well-defined series, from the largest and brightest to the smallest and dimmest, which is called the main sequence. For historical reasons, spectrographers label the types O, B, A, F, G, K, M. (The mnemonic is "Oh, be a fine girl, kiss me.") The series being continuous, a number is added to place each star more exactly on the curve. For example, the F types begin with Fo; then we get Fl, F2, and so on through F9, which is followed by Go. That last, Go, was formerly the classification of our own sun; but more recent information has gotten Sol to be labeled G2.

Figure 1 shows a large part of the main sequence. It omits the extremes, because they really are too extreme to diagram very well. That is, the main sequence runs from the hottest Type O blue giants, some as much as a million times the strength of Sol, on through the yellowish F and G stars, to the red dwarfs of Class M, the dimmest of which may be less than a thousandth as intense as our daystar. Types are indicated along the bottom of the graph, with corresponding masses. Luminosities--necessarily on a logarithmic scale--are shown going up the left-hand side.

From this, you can find the mass corresponding to a given brightness. It will only be a rough estimate; but then, the real values don't lie neatly on an infinitely thin curve. They vary by a fair amount, depending on such factors as the age and exact chemical composition of the individual star.

More is involved than just the total radiation. As everyone knows who has ever heated a piece of metal in a fire, temperature affects color. The hottest stars are called blue giants because they are not only giants in output, but also their light contains a distinctly larger proportion of blue than does that of Sol. They also emit a higher percentage, as well as absolute amount, of ultraviolet and X-ray wavelengths; and no doubt the solar winds streaming from them are something terrific. All these quantities drop off as temperature does, until we get to the cool, ultraviolet poor red dwarfs. (However, the weaker ones among these last are not mere embers. Sometimes they spit out monstrous flares that may temporarily double the total brightness--a fact which I used in a story once but on which I have no copyright.) Well, shall we put our imaginary world in orbit around one of the spectacular giants?

Sorry. Because they burn at such a prodigal rate, these great stars are short-lived. Once they have condensed from interstellar dust and gas, Type O suns spend a bare few million years on the main sequence: then they apparently go out in the supernal violence of supernova explosions. Their ultimate fate, and the precise death throes of their somewhat lesser brethren, are too complicated to discuss here. But even an A0 star like Sirius is good for no more than about four hundred million years of steady shining--not much in terms of geology and evolution.

Furthermore, the evidence is that giants don't have planets in the first place. There is a most suggestive sharp drop in the rotation rate, just about when one gets to the earlier Type Fs. From then on, down through Type M, suns appear to spin so slowly that it is quite reasonable to suppose the "extra" has gone into planets.

Giants are rare, anyway. They are far outnumbered by the less showy yellow dwarfs like Sol--which, in turn, are outnumbered by the inconspicuous red dwarfs. (There are about ten times as many M as G stars.) And this great majority also has the longevity we need. For instance, an F5 spends a total of six billion years on the main sequence before it begins to swell, redden, and die. Sol, G2, has a ten-billion-year life expectancy, and is about halfway through it at the present day, making a comfortingly long future. The K stars live for several times that figure, the weakest M stars for hundreds of billions of years. Even if life, in the biological sense, is slow to get generated and slow to evolve on a planet so feebly irradiated, it will have--or will have had—a vast time in which to develop. That may or may not make a significant difference; and thereby hangs many a tale.

So let's take a star of Type F or later. If we want to give it a planet habitable to man, probably it must be somewhere between, say, Fs and Ks. Earlier in the sequence, the system will presumably be too young for photosynthesis to have started, releasing oxygen into the air. Later, the sun will be too cool, too dull, too niggardly with ultraviolet, to support the kind of ecology on which humans depend.

Granted, a planet of a red dwarf may bear life of another sort than ours. Or it may orbit close enough that the total radiation it gets is sufficient for us. In the latter case, the chances are that it would rotate quite slowly, having been braked by tidal friction. The sun would appear huge and reddish, or even crimson, in the sky; one might be able to gaze straight at it, seeing spots and flares with the naked eye. Colors would look different, and shadows would have blurrier outlines than on Earth. Already, then, we see how many touches of strangeness we can get by changing a single parameter. In the superficially dry data of astronomy and physics is the potential of endless adventure.

But for our concrete example of planet-building, let's go toward the other end of the scale, i.e., choosing a star brighter than Sol. The main reason for doing so is to avoid the kind of complications we have just noticed in connection with a weaker sun. We will have quite enough to think about as isI

The hypothetical planet is one that I recently had occasion to work up for a book to be edited by Roger Elwood, and is used with his kind permission. I named it Cleopatra. While tracing out the course of its construction, we'll look at a few conceivable variations, out of infinitely many.

First, where in the universe is the star? It won't be anywhere in our immediate neighborhood, because those most closely resembling Sol within quite a few light-years are somewhat dimmermours being, in fact, rather more luminous than average. (True, Alpha Centauri A is almost a twin, and its closer companion is not much different. However, this is a multiple system. That does not necessarily rule out its having planets; but the possibility of this is controversial, and in any event it would complicate things too much for the present essay if we had more than one sun.)

Rather than picking a real star out of an astronomical catalogue, though that is frequently a good idea, I made mine up, and arbitrarily put it about four hundred light-years off in the direction of Ursa Major. This is unspecific enough--it defines such a huge volume of space--that something corresponding is bound to be out there someplace. Seen from that location, the boreal constellations are considerably changed, though most remain recognizable. The austral constellations have suffered the least alteration, the equatorial ones are intermediately affected. But who says the celestial hemispheres of Cleopatra must be identical with those of Earth? For all we know, its axis could be at right angles to ours. Thus a writer can invent picturesque descriptions of the night sky and of the images that people see there.

Arbitrary also is the stellar type, F7. This means it has 1.2 times 'the mass of Sol, 20 percent more. As we shall see, the diameter is little greater; but it has 2.05 times the total luminosity.

Numbers this precise cannot be taken off a graph. I computed them on the basis of formulas. But you can get values close enough for most purposes from figure 2. It charts the relevant part of the main sequence on a larger scale than figure 1, and has no need to depict any numbers logarithmically. In other words, with the help of a ruler you can find approximately what mass corresponds to what brightness. Nor is this kind of estimating dishonest. After all, as said before, there is considerable variation in reality. If, say, you guessed that a mass of 1.1 Sol meant an energy output of 1.5, the odds are that some examples of this actually exist. You could go ahead with reasonable confidence. Anyway, it's unlikely that the actual values you picked would get into the story text. But indirectly, by making the writer understand his own creation in detail, they can have an enormous influence for the better.

Returning to Cleopatra: an F7 is hotter and whiter than Sol. Probably it has more spots, prominences, flares, and winds of charged particles sweeping from it. Certainly the proportion of ultraviolet to visible light is higher, though not extremely so.

It is natural to suppose that it has an entire family of planets; and a writer may well exercise his imagination on various members of the system. Here we shall just be dealing with the habitable one. Bear in mind, however, that its nearer sisters will doubtless from time to time be conspicuous in its heavens, even as Venus, Mars, and others shine upon Earth. What names do they have-what poetic or mystical significance in the minds of natives or of long-established colonists?

For man to find it livable, a planet must be neither too near nor too far from its sun. The total amount of energy it receives in a given time is proportional to the output of that sun and inversely proportional to the square of the distance between. Figure 3 diagrams this for the inner solar system in terms of the astronomical unit, the average separation of Sol and Earth. Thus we see that Venus, at 0.77 AU, gets about 1.7 times the energy we do, while Mars, at 1.5 AU, gets only about 0.45 the irradiation. The same curve will work for any other star if you multiply its absolute brightness. For example, at its distance of 1.0 AU, Earth gets 1.0 unit of irradiation from Sol; but at this remove from a sun half as bright, it would only get half as much, while at this same distance from our hypothetical sun, it would get 2.05 times as much.

That could turn it into an oven--by human standards, at any rate. We want our planet in a more comfortable orbit. What should that be? If we set it about 1.4 AU out, it would get almost exactly the same total energy that Earth does. No one can say this is impossible. We don't know what laws govern the spacing of orbits in a planetary system. There does appear to be a harmonic rule (associated with the names of Bode and Titius) and there are reasons to suppose this is not coincidental. Otherwise we are ignorant. Yet it would be remarkable if many stars had planets at precisely the distances most convenient for man.

Seeking to vary the parameters as much as reasonable, and assuming that the attendants of larger stars will tend to swing in larger paths, I finally put Cleopatra 1.24 AU out. This means that it gets 1.33 times the total irradiation of Earth--a third again as much.

Now that is an average distance. Planets and moons have elliptical orbits. We know of none that travel in perfect circles. However, some, like Venus, come close to doing so; and few have courses that are very eccentric. For present purposes, we can use a fixed value of separation between star and planet, while bearing in mind that it is only an average. The variations due to a moderate eccentricity will affect the seasons somewhat, but not much compared to other factors.

If you do want to play with an oddball orbit, as I have done once or twice, you had better explain how it got to be that way; and to follow the cycle of the year, you will have to use Kepler's equal-areas law, either by means of the calculus or by counting squares on graph paper. In the present exposition, we will assume that Cleopatra has a near-circular track.

Is not an added thirty-three percent of irradiation enough to make it uninhabitable?

This is another of those questions that cannot be answered for sure in the current state of knowledge. But we can make an educated guess. The theoretical ("black body") temperature of an object is proportional to the fourth root--the square root of the square root--of the rate at which it receives energy. Therefore it changes more slowly than one might think. At the same time, the actual mean temperature at the surface of Earth is considerably greater than such calculations make it out to be, largely because the atmosphere maintains a vast reservoir of heat in the well-known greenhouse effect. And air and water together protect us from such day-night extremes as Luna suffers.

The simple fourth-root principle says that our imaginary planet should be about 20°C, or roughly 40°F, warmer on the average than Earth is. That's not too bad. The tropics might not be usable by men, but the higher latitudes and uplands ought to be pretty good. Remember, though, that this bit of arithmetic has taken no account of atmosphere or hydrosphere. I think they would smooth things out considerably. On the one hand, they do trap heat; on the other hand, clouds reflect back a great deal of light, which thus never has a chance to reach the surface; and both gases and liquids blot up, or redistribute, what does get through.

My best guess is, therefore, that while Cleopatra will generally be somewhat warmer than Earth, the difference will be less than an oversimplified calculation suggests. The tropics will usually be hot, but nowhere unendurable; and parts of them, cooled by altitude or sea breezes, may well be quite balmy. There will probably be no polar ice caps, but tall mountains ought to have their eternal snows. Pleasant climates should prevail through higher latitudes than is the case on Earth.

You may disagree, in which case you have quite another story to tell. By all means, go ahead. Varying opinions make science fiction yarns as well as horse races.

Meanwhile, though, let's finish up the astronomy. How long is the planet's year? Alas for ease, this involves two factors, the mass of the sun and the size of the orbit. The year-length is inversely proportional to the square root of the former, and directly proportional to the square root of the cube of the semimajor axis. Horrors.

So here we need two graphs. Figure 4 shows the relationship of period to distance from the sun within our solar system. (The "distance" is actually the semi-major axis; but for purposes of calculations as rough as these, where orbits are supposed to be approximately circular, we can identify it with the mean separation between star and planet.) We see, for instance, that a body twice as far out as Earth is takes almost three times as long to complete a circuit. At a remove of 1.24 AU, which we have assigned to Cleopatra, its period would equal 1.38 years.

But our imaginary sun is more massive than Sol. Therefore its gravitational grip is stronger and, other things being equal, it swings its children around faster. Figure 5 charts inverse square roots. For a mass of 1.2 Sol, this quantity is 0.915

If we multiply together the figures taken off these two graphs-1.38 times 0.915--we come up with the number we want, 1.26. That is, our planet takes 1.26 times as long to go around its sun as Earth does to go around Sol. Its year lasts about fifteen of our months.

Again, the diagrams aren't really that exact. I used a slide rule. But for those not inclined to do likewise, the diagrams will furnish numbers that can be used to get at least a general idea of how some fictional planet will behave.

Let me point out afresh that these are nevertheless important numbers, a part of the pseudo-reality the writer hopes to create. Only imagine: a year a fourth again as long as Earth's. What does this do to the seasons, the calendar, the entire rhythm of life? We shall need more information before we can answer such questions, but it is not too early to start thinking about them.

Although more massive than Sol, the sun of Cleopatra is not much bigger. Not only is volume a cube function of radius, which would make the diameter just six percent greater if densities were equal, but densities are not equal. The heavier stars must be more compressed by their own weight than are the lighter ones. Hence we can say that all suns that more or less resemble Sol have more or less the same size.

Now our imaginary planet and its luminary are further apart than our real ones. Therefore the sun must look smaller in the Cleopatran than in the terrestrial sky. As long as angular diameters are small (and Sol's, seen from Earth, is a mere half a degree) they are closely enough proportional to the linear diameters and inversely proportional to the distance between object and observer. That is, in the present case we have a star whose breadth, in terms of Sol, is 1, while its distance is 1.24 AU. Therefore the apparent width is 1/1.24, or 0.807 what Sol shows to us. In other words, our imaginary sun looks a bit smaller in the heavens than does our real one.

This might be noticeable, even striking, when it was near the horizon, the common optical illusion at such times exaggerating its size. (What might the psychological effects of that be?) Otherwise it would make no particular difference--since no one could safely look near so brilliant a thing without heavy eye protection--except that shadows would tend to be more sharpedged than on Earth. Those shadows ought also to have a more marked bluish tinge, especially on white surfaces. Indeed, all color values are subtly changed by the light upon Cleopatra. I suspect men would quickly get used to that; but perhaps not.

Most likely, so active a sun produces some auroras that put the terrestrial kind to shame, as well as occasional severe interference with radio, power lines, and the like. (By the time humans can travel that far, they may well be using apparatus that isn't affected. But there is still a possible story or two in this point.) An oxygen-containing atmosphere automatically develops an ozone layer that screens out most of the ultraviolet. Nevertheless, humans would have to be more careful about sunburn than on Earth, especially in the lower latitudes or on the seas.

Now what about the planet itself?. If we have been a long time in coming to that, it simply emphasizes the fact that no body - and nobody--exists in isolation from the whole universe.

Were the globe otherwise identical with Earth, we would already have innumerable divergences. Therefore let us play with some further variations. For instance, how big or small can it be? Too small, and it won't be able to hold an adequate atmosphere. Too big, and it will keep most of its primordial hydrogen and helium, as our great outer planets have done; it will be even more alien than are Mars or Luna. On the other hand, Venus-with a mass similar to Earth's--is wrapped in gas whose pressure at the surface approaches a hundred times what we are used to. We don't know why. In such an area of mystery, the science fiction writer is free to guess.

But let us go at the problem from another angle. How much gravity--or how little--can mankind tolerate for an extended period of time? We know that both high weight, such as is experienced in a centrifuge, and zero weight, such as is experienced in an orbiting spacecraft, have harmful effects. We don't know exactly what the limits are, and no doubt they depend on how long one is exposed. However, it seems reasonable to assume that men and women can adjust to some such range as 0.75 to 1.25 Earth gravity. That is, a person who weighs 150 pounds on Earth can safely live where he weighs as little as 110 or as much as 190. Of course, he will undergo somatic changes, for instance in the muscles; but we can suppose these are adaptive, not pathological.

(The reference to women is not there as a concession to militant liberationists. It takes both sexes to keep humanity going. The Spaniards failed to colonize the Peruvian altiplano for the simple reason that, while both they and their wives could learn to breathe the thin air, the wives could not bring babies to term. So the local Indians, with untold generations of natural selection behind them, still dominate that region, racially if not politically. This is one example of the significance of changing a parameter. Science fiction writers should be able to invent many more.)

The pull of a planet at its surface depends on its mass and its size. These two quantities are not independent. Though solid bodies are much less compressible than gaseous ones like stars, still, the larger one of them is, the more it tends to squeeze itself, forming denser allotropes in its interior. Within the man-habitable range, this isn't too important, especially in view of the fact that the mean density is determined by other factors as well. If we assume the planet is perfectly spherical--it won't be, but the difference isn't enough to worry about except under the most extreme conditions--then weight is proportional to the diameter of the globe and to its overall density.

Suppose it has 0.78 the (average) Terrestrial diameter, or about 6,150 miles; and suppose it has 1.10 the (mean) Terrestrial density, or about 6.1 times that of water. Then, although its total mass is only 0.52 that of Earth, about half, its surface gravity is 0.78 times 1.10, or 0.86 that which we are accustomed to here at home. Our person who weighed 150 pounds here, weighs about 130 there.

I use these particular figures because they are the ones I chose for Cleopatra. Considering Mars, it seems most implausible that any world that small could retain a decent atmosphere; but considering Venus, it seems as if many worlds of rather less mass than it or Earth may do so. At least, nobody today can disprove the idea.

But since there is less self-compression, have I given Cleopatra an impossibly high density? No, because I am postulating a higher proportion of heavy elements in its makeup than Earth has. This is not fantastic. Stars, and presumably their planets, do vary in composition.

(Writers can of course play with innumerable other combinations, like that in the very large but very metal-poor world of Jack Vance's Big Planet.)

The results of changing the gravity must be far-reaching indeed. Just think how this could influence the gait, the need for systematic exercise, the habit of standing versus sitting (are people in low weight more patient about queues?), the character of sports, architecture, engineering (the lower the weight, the smaller wings your aircraft need under given conditions, but the bigger brakes your ground vehicles), and on and on. In a lesser gravity, it takes a bit longer to fall some certain distance, and one lands a bit less hard; mountains and dunes tend to be steeper; pendulums of a given length, and waves on water, move slower. The air pressure falls of less rapidly with altitude. Thus, here on Earth, at about 18,000 feet the pressure is one half that at sea level; but on Cleopatra, you must go up to 21,000 feet for this. The effects on weather, every kind of flying, and the size of life zones bear thinking about.

A higher gravity reverses these consequences, more or less in proportion.

In our present state of ignorance, we have to postulate many things that suit our story purposes but may not be true--for example, that a planet as small as Cleopatra can actually hold an Earth-type atmosphere. Other postulates--for example, that Cleopatran air is insufficient, or barely sufficient, to sustain human life--are equally legitimate, and lead to quite other stories. But whatever the writer assumes, let him realize that it will make for countless strangenesses, some radical, some subtle, but each of them all-pervasive, in the environment.

(I must admit that certain of them scarcely look important. Thus, the horizon distance--for a man standing on a flat plain-is proportional to the square root of the planet's diameter. On Earth it is about five miles, and for globes not very much bigger or smaller, the change will not be striking. Often mountains, woods, haze, or the like will blot it out entirely .... Yet even in this apparent triviality, some skillful writer may see a story.)

If we have a higher proportion of heavy elements, including radioactive ones, than Earth does, then we doubtless get more internal heat; and the lesser size of Cleopatra also helps pass it outward faster. Thus here we should have more than a terrestrial share of volcanoes, quakes, and related phenomena. I guess there would be plenty of high mountains, some overreaching Everest; but we still know too little about how mountains get raised for this to be much more than a guess. In some areas, local concentrations of arsenic or whatever may well make the soil dangerous to man. But on the whole, industry ought to thrive.

Conversely, and other things being equal, a metal-poor world is presumably fairly quiescent; a shortage of copper and iron might cause its natives to linger indefinitely in a Stone Age; colonists might have to emphasize a technology based on lighter elements such as aluminum. How fast does the planet rotate? This is a crucial question, but once more, not one to which present-day science can give a definitive answer. We know that Earth is being slowed down by Luna, so maybe it once spun around far more quickly than now. Maybe. It isn't being braked very fast, and we can't be sure how long that rate of deceleration has prevailed in the past or will in the future. Mars, whose satellites are insignificant, turns at nearly the same angular speed, while Venus, with no satellite whatsoever, is exceedingly slow and goes widder shins to boot.

It does seem likely that big planets will, by and large, spin rapidly--such as Jupiter, with a period of about ten hours. They must pick up a lot of angular momentum as they condense, and they don't easily lose it afterward. But as for the lesser bodies, like Earth, we're still mainly in the realm of speculation.

I assumed Cleopatra has no satellites worth mentioning. Therefore it has been slowed less than Earth, its present rotation taking 17.3 hours. This makes its year equal to 639 of its own days. But I could equally well have dreamed something different.

If it did have a moon, how would that affect things? Well, first, there are certain limitations on the possibilities. A moon can't be too close in, or it will break apart because of unbalanced gravitational forces on its inner and outer sides. This boundary is called Roche's limit, after the astronomer who first examined the matter in detail. For Earthlike planets it is about 2.5 radii from the center, 1.5 from the surface. That is, for Earth itself Roche's limit is roughly six thousand miles straight up. (Of course, it doesn't apply to small bodies like spaceships, only to larger and less compact masses such as Luna.) On the other hand, a moon circling very far out would be too weakly held; in time, the tug of the sun and neighbor planets would cause it to drift elsewhere. At a quarter million miles' removed, Luna is quite solidly held. But one or two million might prove too much in the long run--and in any event, so remote, our companion would not be a very interesting feature of our skies.

(Cleopatra did have a small moon once, which got too near and disintegrated, forming a ring of dust and rocky fragments. But the calculations about this, to determine what it looks like and how that appearance varies throughout the year, are rather involved.)

Within such bounds, as far as science today can tell, we are free to put almost anything that isn't outrageously big. But if the orbit is really peculiar, the writer should be prepared to explain how this came about. A polar or near-polar track is less stable than one that isn't far off the plane of the ptimary's equator; it is also much less likely to occur in the first place. That is, through some such freak of nature as the capture of an asteroid under exactly the right circumstances, we might get a moon with a wildly canted orbital plane; but it probably wouldn't stay there for many million years. In general, satellites that don't pass very far north and south of the equators of their planets are more plausible.

Well, so let's take a body of some reasonable size, and set it in motion around our imaginary world at some reasonable average distance. (This is distance from the center of the planet, not its surface. For a nearby companion, the distinction is important.) How long does it take to complete a circuit and how big does it look to someone on the ground?

The same principles we used before will work again here. Take figures 4 and 5. Instead of letting "1.0" stand for quantities like "the mass of Sol," "the mean distance of Earth from Sol," and "the period of Earth around Sol," let it stand for "the mass of Earth, ... the mean distance of Luna from Earth," and "the period of Luna around Earth." Thus you find your answer in terms of months rather than years. (This is a rough-and-ready method, but it will serve fairly well provided that the satellite isn't extremely big or extremely near.) Likewise, the apparent size of the object in the sky, compared to Luna, is close-enough equal to its actual diameter compared to Luna, divided by its distance from the surface of the planet, compared to Luna.

But in this case, we aren't done yet. What we have been discussing is the sidereal period, i.e., the time for the satellite to complete an orbit as seen from out among the stars. Now the planet is rotating while the moon revolves around it. Most likely both move in the same direction; retrograde orbits, like polar ones, are improbable though not altogether impossible. Unless the moon is quite remote, this will have a very marked effect. For instance, Luna, as seen from Earth, rises about fifty minutes later every day than on the previous day--while an artificial satellite not far aloft comes up in the west, not the east, and virtually flies through the heavens, undergoing eclipse in the middle of its course.

I would offer you another graph at this point, but unfortunately can't think of any that would be much help. You shall have to subtract revolution from rotation, and visualize how the phases of the moon(s) proceed and how they show in the skies. Bear in mind, too, that very close satellites probably won't be visible everywhere on the planet. Algebra and trigonometry are the best tools for iobs of this kind. But failing them, scale diagrams drawn on graph paper will usually give results sufficiently accurate for storytelling purposes.

The closer and bigger a moon is, the more tidal effect it has. For that matter, the solar tides aren't generally negligible; on Earth they amount to a third of the total. There is no simple formula. We know how tides can vary, from the nearly unmoved Mediterranean to those great bores which come roaring up the Bay of Fundy. Still, the writer can get a rough idea from this fact: that the tide-raising power is proportional to the mass of the moon or sun, and inversely proportional to the cube of its distance. That is, if Luna were twice as massive at its present remove, the tides it creates would be roughly twice what they really are. If Luna kept the same mass but were at twice its present distance, its tides would be 1/23 or one-eighth as strong as now, while if it were half as far off as it is, they would be 23 or eight times as great. In addition, the theoretical height of a deepwater tide is proportional to the diameter and inversely proportional to the density of the planet being pulled upon. That is, the larger and/ or less dense it happens to be, the higher its oceans are lifted. As I said, there is such tremendous local variation that these formulas are only good for making an overall estimate of the situation. But it is crucial for the writer to do that much. How do the waters behave? (Two or more moons could make sailing mighty complicated, not to speak of more important things like ocean currents.) Great tides, long continued, will slow down the rotation--though the amount of friction they make depends also on the pattern of land distribution, with most energy being dissipated when narrow channels like the Bering Strait are in existence. We must simply guess at the effects on weather or on life, but they are almost certainly enormous. For instance, if Earth had weaker tides than it does, would life have been delayed in moving from the seas onto dry ground?

One clear-cut, if indirect, influence of tides on weather is through the spin of the planet. The more rapidly it rotates, the stronger the cyclone-breeding Coriolis forces. In the case of Cleopatra, we have not only this factor, but also the more powerful irradiation--and, maybe, the greater distance upward from surface to stratosphere, together with the lesser separation of poles and tropics--to generate more violent and changeable weather than is common on Earth.

Insofar as the matter is understood by contemporary geophysicists, we can predict that Cleopatra, having a hotter molten core and a greater rate of rotation, possesses a respectable magnetic field, quite likely stronger than the Terrestrial. This will have helped preserve its atmosphere, in spite of the higher temperatures and lower gravity. Solar particles, which might otherwise have kicked gas molecules into space, have generally been warded off. To be sure, some get through to the uppermost thin layers of air, creating secondary cosmic rays, electrical disturbances, and showy auroras.

The weather is likewise affected by axial tilt. Earth does not ride upright in its orbit; ilo member of the Solar System does. Our axis of rotation slants about 23.58 off the vertical. From this we get our seasons, with everything that that implies. We cannot

tell how often Earthlike worlds elsewhere have radically different orientations. My guess is that this is a rarity and that, if anything, Earth may lean a bit more rakishly than most. But it's merely another guess. Whatever value the writer chooses, let him ponder how it will determine the course of the year, the size and character of climatic zones, the development of life and civilizations.

If Earth did travel upright, thus having no seasons, we would probably never see migratory birds across tile sky. One suspects there would be no clear cycle of the birth and death of vegetation either. Then what form would agriculture have taken? Society? Religion?

It is questions like these that science fiction is uniquely well fitted to ask. Simple permutations of natural law, such as we have been considering here, raise amazingly many of them, and suggest tentative answers.

True, this kind of back grounding work is the barest beginning. The writer must then go on to topography, living creatures both non-human and human, problems and dreams, the story itself-ultimately, to those words that are to appear on a printed page. Yet if he has given some thought and, yes, some love to his setting, that will show in the words. Only by making it real to himself can he make it, and the events that happen within its framework, seem real to the reader.

The undertaking isn't unduly hard. It is mind-expanding in the best sense of that phrase. Or may I end by repeating myself and saying that, for writer and reader alike, it's fun?