Electricity and Magnetism? (Part 1)

Riding on an electron: a relativistic approach to the nature of magnetism

by "Cathode Ray"

From a literary quiz: Which book title has been chosen by the largest number of authors?

My guess would be "Electricity and Magnetism". For this purpose I think we might be allowed to include all those who, either to display their striking originality or possibly their sense of priorities, chose "Magnetism and Electricity". These unadorned titles have appeared on the covers of quite a large number of different books, and if we added (as well we might) those really vain attempts to disguise the essential sameness of the subject matter by such expressions as "Elementary . . .", "Introduction to . . ." (a favourite device for the more advanced and difficult treatises), "Short Course on . . .", ". . . for Beginners", etc., the total would be quite formidable.

Why is it that these two things are as inseparable as bacon and eggs or Morecambe and Wise? Or rather, have become so? For both were well known separately for thousands of years as curious but unconnected phenomena. During all that time electricity was noticed as mysterious attractions and repulsions, and even sparks, when certain substances (such as amber—Greek: *elektron*) were rubbed together. This was what we call static electricity—the segregation of unlike charges. Current electricity came much later and at first was not identified as having anything to do with it. Magnetism was noticed in the naturally-occurring iron-bearing mineral lodestone, and was named after the Aegean district of Magnesia, where lodestone was found. It too was an affair of attractions and repulsions, and when magnetism and static electricity began to be studied scientifically (17th and 18th centuries) it was found that they conformed to similar laws, notably the laws of inverse squares.

Meanwhile, current electricity had been discovered, and in 1820 Oersted established the first link-up by showing that electric currents produced magnetic effects. Ampère, with prophetic insight, surmised that the magnetic effects of lodestone and other permanent magnets might also be due to electric currents, on a sub-microscopic scale within the magnet material. (This, though much later it proved to be true, must have seemed most unlikely at the time, as electric currents needed batteries to produce them, and of course the electrical nature of matter was then unknown.)

Faraday tried to perform the reverse experiment, to produce an electric current by a magnet. He was unable to do this with a stationary magnet, but in 1931 he made the discovery that an electric current could be produced by a *moving* magnet, and in so doing he laid the foundation stone of electrical engineering. He also did quite a bit towards proving that current electricity is just static electricity in motion, so that they are essentially the same thing.

The link between electricity and magnetism was tightened when Moxwell produced his famous equations defining electromagnetic waves. More recently, in a television broadcast, the late Sir Lawrence Bragg remarked that magnetism is electricity looked at sideways. And so we come to the question: Are electricity and magnetism closely related but fundamentally separate things? Or are they two aspects of one thing, and if so what thing?

Does it matter? Scientifically it certainly does, and even people who have no interest in science that is just theoretical and academic must admit that today's useful things have come out of yesterday's abstract theory. Scientific progress is often made by putting together isolated facts and finding that they fit, like a jigsaw puzzle, into some general design. Newton made a big step forward when he found that a lot of pieces fitted together into a Law of Universal Gravitation. This seemed to be one of those things that had to be accepted as fundamental, rather than following from something else. But Einstein (of whom more anon) came along with his General Theory of Relativity, in which gravitation was a side effect. The rest of his life he was searching for a still more unified design.

Much in all those books on Electricity and Magnetism is devoted to expounding the relationships between the two things. They appear as equal partners in a beautifully symmetrical system of mutual support. Oersted showed that (what was later discovered to be) moving electric charges caused magnetism, and Faraday showed that moving or varying magnetism caused electricity. In radio waves a moving electric field is creating a moving magnetic field, and the moving magnetic field is creating the moving electric field, and who is to say which comes first or is the more fundamental?

The most significant thing that both do is to produce forces. The lodestone attracted iron filings, and the rubbed amber or glass attracted pith balls or bits of paper. These forces are independent of matter between the attracted bodies; they occur even across empty space. Which is very mysterious indeed.

We try to disguise our ignorance by saying that the forces are due to electric and magnetic fields. But while that is convenient for discussing the facts, it adds nothing to knowledge. Although electric and magnetic fields (and forces) are similar to one another in many respects, there are some essential differences.

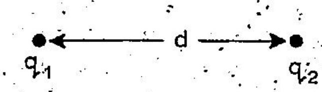

Fig. 1. q_1 and q_2 represents two electric charges concentrated at points. The force between them is proportional to $q_1 q_2/d^2$.

The starting point is Coulomb's law, which says that two isolated point charges, q_1 and q_2 in Fig. 1, separated by distance d, exert a force on one another proportional to

$$\frac{q_1 q_2}{d^2}$$

If the charges are of the same sign the force repels them from one another; if unlike, it attracts. Although there are no such things as point charges, electrons and even positive ions are very close approximations to them.

From the principle that the total force on a charge is the vector sum of all those acting, one can work out the forces between other configurations of charges, such as parallel plates. For convenience it is all done in terms of the fields that are said to surround charges. One isolated point or spherical charge has a radial field; parallel plates have a uniform field; etc. The force on a point charge in an electric field is proportional to the strength of the charge and the intensity of the field (without the charge).

Theoretically there is a counterpart of Coulomb's law in magnetism, but it suffers the serious disadvantage that in practice there is nothing even approximately like an isolated magnetic pole at a point. However, one gets magnetic fields of the same shapes as electric fields, and the forces work on the same principles.

Coming now to the link-up, we note that a magnetic field has no effect on a stationary charge, but directly the charge moves it experiences a force. That is because a moving charge (usually one of many forming a procession called an electric current) generates a magnetic field, which reacts with the magnetic field already there, just as the electric fields of q_1 and q_2 react on one another. So if two charges move relative to one another they experience forces due to both electric and magnetic fields. This makes things rather complicated. But in practice we are interested in moving charges most often when they are currents in wires or some other conductor. Here each moving negative charge (electron) is exactly offset electrically by a positive charge fixed in the structure of the wire. So the wire as a whole is electrically neutral, and the forces that current-carrying wires exert on one another are wholly magnetic.

Correspondingly, when magnets move they cause electric fields. We rely on this very heavily, as it is the principle on which power stations work.

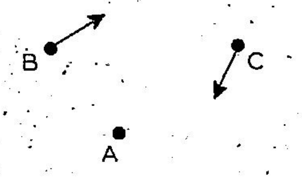

Fig. 2. Two point charges at B and C are moving relative to one another. The accounts given of this state of affairs by observers B fixed to B, C fixed to C, and A stationary at A, disagree fundamentally.

In trying to summarize Electricity and Magnetism in a few paragraphs I have omitted to specify just what is meant by "moving". Take the two "moving" charges, B and C in Fig. 2. So far as an observer A is concerned they are both moving, but if observer B happens to be travelling along with one of them he will say it is at rest and only the other charge is moving. So his charge can't be causing a magnetic field, so it can't affect or be affected by the other charge magnetically. A disagrees totally with this. Observer C travelling with the other charge agrees with B so far as the absence of any magnetic reaction is concerned, but disagrees flatly with him on which charge is causing the magnetic field that all three agree is present.

It should be clear from this example that until we can sort out this problem the study of Electricity and Magnetism is futile.

One thing we can say definitely is that the velocities of charge-carrying and magnet-carrying objects, and the kind (electric or magnetic) and strength of any field present, depend on the state of motion or non-motion of the instruments used for observing these things.

I started writing this article in November 1962. No; I didn't forget about it or lose it. I've been trying all this time (on and off!) to answer the title question without letting down those kind people who tell me they can understand most of what I write. All the treatises I could find on the subject were either in the mathematical stratosphere or were too vulnerable to the persistent questioner. Even now I fear you may find I have just added to the number of these.

Imagine that there are two observers, equipped with means for measuring strength and direction of electric field (E) and magnetic field (H) or, more likely, magnetic flux density B, which is equal to μH, μ being the local permeability. They are operating in the gap between the poles of a vast magnet (Fig. 3) which maintains

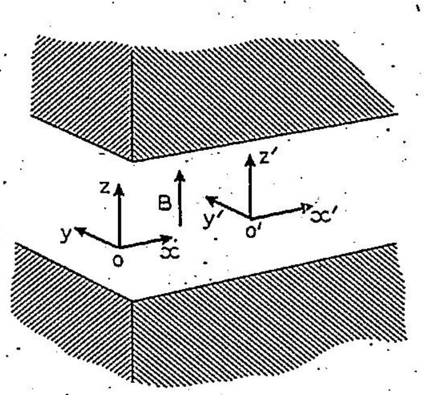

Fig. 3. Two observers, O and O', are measuring electric and magnetic fields between the poles of an extensive magnet. O' is moving along direction x with velocity v relative to O. They too disagree over their findings.

a uniform B vertically upward. Observer O is stationary relative to the magnet, but O' is moving away from him with constant velocity v. As fields are three-dimensional, the observers need to agree on their "frames of reference", having x, y and z axes all mutually at right angles as shown. And to make things as simple as possible x', y' and z' are parallel to x, y and z, and O' is moving along x which is in the same line as x'.

O reports that there is a positive B along his positive z axis, none along x or y, and no E at all. O' reports the same with one exception. His y' axis is cutting the magnetic flux. The well-known electrical engineers' generator rule predicts an e.m.f. e equal to Bvl, where l is the length of a conductor cutting the flux. But the e.m.f. is the result of a field E equal to e/l, which exists by virtue of the motion in B, whether there is a conductor or not. So O' finds an electric field along the y' axis, and Fleming's right-hand rule tells us that it will be negative along $+y'$. In his shorthand he would say

$$E'_y = -vB_z$$

or, since the counterpart of E is H,

$$E'_y = -v\mu H_z$$

If there was also an electric field along the same axis, E_y, detectable by O, the total E'_y would be $E_y - v\mu H_z$. And if there was a magnetic field H_y and also an E_z, by the same arguments we would be able to say

$$E'_z = E_z + v\mu H_y$$

But any magnetic component along x would not be cut by movement in that direction, so E'_x would be the same as E_x, if any. Putting all these together we get

$$E'_x = E_x;\ E'_y = E_y - v\mu H_z;$$
$$E'_z = E_z + v\mu H_y \qquad (1)$$

Next we ask O' for a magnetic report. Having already considered the possible existence of an electric field specified in magnitude and direction by E_x, E_y and E_z, we must be prepared to hear that O' finds his movement through such a field causes magnetic effects unknown to O. Suppose, for example, that the lower pole-piece was charged positively and the upper one negatively, so that there was a positive E_z. O' would have reported this, along with anything due to cutting a y component of magnetic field, as in (1). But, unlike O, he would see the + and − charges moving past him in the $-x'$ direction. So far as he was concerned they would be electric currents, and the cork-screw rule tells us he would see a magnetic field due to these currents, along the y' axis. Reference to the textbooks would confirm the O' report of a magnetic field equal to $v\epsilon E_z$ along the $+y$ axis, ϵ being the local permittivity. This is in addition to any H_y noted by O. Similarly, any E_y would give rise to a magnetic field $-v\epsilon E_y$ along z besides any H_z noted by O. But the existence of an electric field along x is not seen by O' as a current, so $H'_x = H_x$.

Putting these together we have

$$H'_x = H_x;\ H'_y = H_y + v\epsilon E_z;$$
$$H'_z = H_z - v\epsilon E_y \qquad (2)$$

(1) and (2) together are a complete formula for predicting how any combination of fields we see will look to someone else moving away from us with constant velocity v. If he happens to be moving towards us, that is covered by a negative value of v. And if his movement is not along or parallel to our x axis, then all we have to do is reorient both our frames of reference so that he is.

After that achievement we may be tempted to put it away for (improbable) future reference. But if we have the true scientific insistence on cross-checking everything, we (O) will change places with O' and solve our set of equations (1) and (2) for E and H, to see how our observations E' and H' will look to the new Mr O. For example, we pick out from (1)

$$E'_y = E_y - v\mu H_z$$

and from it immediately get

$$E_y = E'_y + v\mu H_z \qquad (3)$$

Then, to deal with H_z we pick out from (2)

$$H'_z = H_z - v\epsilon E_y$$

which gives us

$$H_z = H'_z + v\epsilon E_y$$

and substituting this in (3) we get

$$E_y = E'_y + v\mu H'_z + v^2\mu\epsilon E_y$$

So

$$E_y(1 - v^2\mu\epsilon) = E'_y + v\mu H'_z$$

and

$$E_y = \frac{E'_y + v\mu H'_z}{1 - v^2\mu\epsilon} \qquad (4)$$

If we are in empty space, μ and ϵ will be μ_0 and ϵ_0, the permeability and permittivity of space, or the space constants as one ought to call them. (For our comfort, almost the same values apply to air.) One of their basic relationships is,

$$\mu_o \epsilon_o = \frac{1}{c^2}$$

c being the speed of light in space. So we can substitute $(1-v^2/c^2)$ for $(1-v^2\mu\epsilon)$.

Either way, this result is very disturbing. When we changed places with O' we saw O moving with velocity $-v$ along our axis x'. Working out the equations for E and H as we did for E' and H' from position O we would expect them to be the same except for the reversal in sign of v and the interchange of dashed and undashed letters. That is indeed true of (4) except for the factor $(1-v^2\mu_o\epsilon_o)$ or $1(1-v^2/c^2)$. We will find this same factor intrudes into every equation involving v. But it oughtn't to! There is a downright contradiction between the results of solving equations (1) and (2) to give E and H in terms of E' and H', which gives us the intruder every time, and deriving the inverse equations for E and H in the same way as we derived those for E' and H'.

This is quite mad and impossible! Unless perchance the value of the intruder turns out to be 1. But it only is when $v=0$! Admittedly any practical velocity even up to rocket speeds is so much less than the speed of light that the discrepancy would seem to be negligible. But there oughtn't to be *any* discrepancy between what O sees of O' and O' sees of O, apart from the reversal of v!

At least we can get rid of the lack of balance between the sets of equations, (1) and (2), and their E and H counterparts if we split the intruder into two equal parts by taking its square root and attaching this to *all* the equations. For convenience we can give this half-intruder a single symbol, β:

$$\beta = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

Then our original (1) and (2) become

$$\left.\begin{array}{l} E'_x=E_x;\ E'_y=\beta(E_y-v\mu H_z);\ E'_z=\beta(E_z+v\mu H_y) \\ H'_x=H_x;\ H'_y=\beta(H_y+v\epsilon E_z);\ H'_z=\beta(H_z-v\epsilon E_y) \end{array}\right\} \quad (5)$$

and if we derive from these their E and H counterparts, either by solving the above simultaneous equations or by reversing the sign of $-v$ to take account of the reversal of viewpoint, we get a set corresponding to (5), with the factor β in the same places.

That gives them a nice symmetrical appearance, but how can we justify the insertion of β when it has no place in the well-tried laws of electro-magnetic induction which we used to arrive at (1) and (2)?

It must be admitted that we are not the first people to puzzle over this. As long ago as 1895 the physicist Lorentz had reached the conclusion that the laws of electricity and magnetism needed to be supplemented by β before the estimates made by observers in motion relative to one another could be reconciled.

This was one of the pieces that Einstein put together a few years later to compose his Special (or Restricted) Theory of Relativity. Velocity is, of course length divided by time, and Einstein showed that the behaviour of Nature could not be accounted for exactly if the basic quantities length, time and mass were, as hitherto assumed, independent of their relative motion. You can hardly expect me to insert a complete treatise on this rather involved subject right here, but there is a simple explanation in "The Electron in Electronics", by M. G. Scroggie, Chap. 10 (Butterworth, 1965). The main results are:

(1) Bodies moving relative to the observer appear to him to have shrunk in the direction of motion by the factor $1/\beta$.

(2) The time interval between two events occurring in a system in motion relative to an observer appears to him longer by the factor β than it does to an observer moving with it.

(3) A moving mass appears β times greater than the same mass at rest relative to the observer.

(4) Because no frame of reference has any "absolute" status, all have equal status, so while observer A sees B's spaceship has shrunk in the direction he is going, according to (1) above, B notices exactly the same thing about A's. Assuming they have identical models, each sees the other's ship is shorter and heavier than his own and his clocks run slower.

All very well, you may say, but aren't we moving at rather high velocity away from our question of which comes first, the electric egg or the magnetic chicken?

Well, frankly, no. We shall be needing Lorentz-Einstein before we've finished. Meanwhile it may encourage us on our way to note that we already have an answer to the title question. It is the very basis of relativity that no frame of reference has any higher status than another; in other words, all velocities are relative—there can be no fixed point from which to reckon absolute velocity. So although in Fig. 3 Mr O says there is no electric field, Mr O' says there is, and both are equally right. Although therefore it is in practice convenient to have the separate names "electricity" and "magnetism", they are parts of one whole, in the way Bragg meant.

As to priority, electricity must be a hot favourite. Electric charges are things that are there and can be manipulated one by one. Unlike those apparently absolute things, length, time and mass, electric charge is absolute and unaffected by velocity or anything else. It needs no magnetic or other action to bring it into existence.

How about electric power generators, which depend on moving magnets? Well, it is true that they need these for separating already existing charges of opposite sign. But it is not the only way of doing that—there are such things as batteries and rapidly-taken-off nylon underwear—and anyway the magnets rely wholly on electric currents in the first place. Even permanent magnets owe their magnetism to internal electrical action.

So we can conclude that electricity is the fundamental thing and magnetism a by-product.

Can one go even further than that and say that the two things are the same—the forces that pull magnets together and activate magnetic compasses and pull electric motors round (or, in the case of Professor Eric Laithwaite, straight along) are identical with the electrostatic forces that draw pith balls and gold leaves together in electroscopes and make the rapidly-taken-off vest behave as if it was trying to get back on again?

This seems obviously going too far; if it were so, how is it that one can distinguish between electric and magnetic fields? An electrically charged droplet placed in an electric field is urged thereby into motion, but if placed in a magnetic field it takes no notice.

This delicately poised state of our inquiry is perhaps the right moment at which, as Reginald Bosanquet would say, to take the break. Be with us in Part 2 to see the answer to the question, how is it possible to hold that things which can be distinguished are the same.

Sixty Years Ago

The leader page of the September 1914 issue voiced a problem which has recently become a familiar one again but for a different reason. "Our readers will notice that the present issue is a slimmer volume . . . due to the anticipated shortage of printing paper, which is one of the consequences of the war."

Elsewhere in the issue the war occasionally sank into the background. K.K.G., relating his experiences with a kite aerial, "Found that a two-foot kite would take with ease a 36-gauge 600-foot aerial in a normal wind and keep it there without any trouble. A stouter aerial is somewhat better, but has the disadvantage of requiring a larger kite, and should a gust of wind raise the kite suddenly there is a danger of its soaring off with the receiving set."

Finally, who can argue with the unfathomable depths of wisdom which concluded a piece on psychology and telegraphy "In conclusion, the sub-conscious mind may be likened to the phonograph. The impression made upon the wax record has a conscious source, and from the record it is reproduced mechanically" . . . Pardon?

Corrections

"Electronic ignition techniques". In the article of the above title in our July issue the address given for Future Tecmatics in reference No. 6 should be 4 Arkwright Road, Launton Industrial Estate, Bicester, Oxon.

In the article **"Coloursound System"**, by J. R. Penketh, May 1974, pin 4 of the first amplifier in Fig. 7 should be connected to line 10 not 9.

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Basics and relevance of techniques for the Radio Amateur with introductory construction details

by P. I. Day, B.A.
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A short article on the basics of transmission lines, including a derivation of several equations. Construction details will be of interest to anyone considering building circuits in stripline form. The title is based on a suggestion by Francis Crick, recorded in the book *The Double Helix*, by James Watson, that he would write a book on Fourier Transforms for the non-mathematician to be entitled "Fourier Transforms for the Birdwatcher".

For many years considerable effort has been devoted by the electronics industries and research laboratories throughout the world to developing and perfecting transmission systems capable of handling the rapidly increasing communications traffic. Britain, France, America and Japan amongst others are developing systems which will operate on overmoded TE_{01} circular waveguides in the range 30–130GHz, the intermediate frequencies for this equipment lying in the range 1–5GHz. This is a compromise between the bandwidth needed to cope with projected rates of digital transmission per channel and the rapidly increasing costs of amplifiers as the frequency is raised. Japan has chosen a starting frequency of 4GHz whereas Britain has chosen 1.25GHz. Many of the techniques involved at these lower frequencies have applications in the Radio Amateur bands at 23cm and above which at present are little used. The frequency range quoted is conveniently covered by stripline or microstrip, the lower frequency being limited by size considerations of the distributed elements, the upper by losses which can rise rapidly with the substrate materials available for amateur use at a reasonable price.

Fig. 1 shows the method of construction of three types of transmission line which may be used at these frequencies; triplate and coaxial lines have the disadvantages that the final circuit form is relatively permanent, not easily adjustable and difficult for mounting discrete components. None of these disadvantages apply to stripline and for this reason it has been chosen as the transmission medium. In addition, its construction is compatible with printed circuit techniques which are already familiar to many people.

A transmission line may be characterized by two quantities, impedance and propagation constant. These can be understood by considering an infinite length of line. On applying a voltage to one end of the line, a wavefront will propagate down the line at a speed and with an attenuation determined by the propagation constant. The current flowing into the line is simply the voltage divided by the characteristic impedance. If we now apply a sinewave to this line, two points separated by a distance x will have a phase difference between them of $2\pi x/\lambda_m$ at any instant of time; λ_m is the wavelength in the transmission line at the applied frequency. There will also be an attenuation in amplitude. These two components are combined by stating that the wave propagates as $e^{-\gamma x}$, where $\gamma=\alpha+j\beta$, $e^{-\gamma x}$ is the attenuation component, α measured in Nepers/metre and $e^{-\beta x}$ is the phase variation, $2\pi/\lambda_m$ radians/metre.

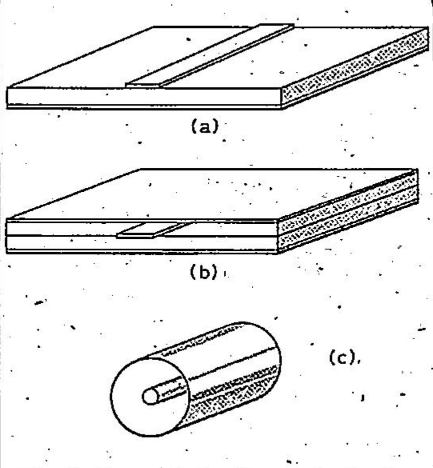


Fig. 1. Transmission line methods of construction (a) stripline, (b) triplate, (c) coaxial.

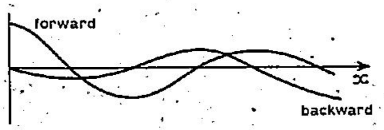


Fig. 2. Forward and backward reflected waves on a transmission line.

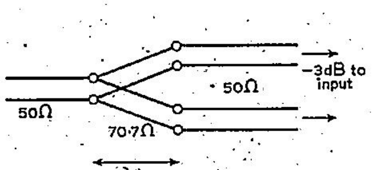


Fig. 3. Simple means of forming a power splitter.

Fig. 2 shows an example of a forward propagating wave, and a wave travelling in the reverse direction due to a generator at the opposite end of the line which will progress as $e^{\gamma x}$. Due to these two waves we will have a total voltage and current at any point on the line given by

$$V_T=V_+e^{-\gamma x}+V_-e^{\gamma x}$$

$$I_TZ_0=V_+e^{-\gamma x}-V_-e^{\gamma x} \quad \ldots\ldots\ldots (10)$$

The voltage measured across the line is in the same sense for both waves, whereas the current flowing is of opposite sense. For our purposes we can usually neglect the attenuation of the line and consider only the phase variations.

In the Appendix the impedance has been derived at the input to a line terminated by an arbitrary load. From this we will consider four conditions of termination which are of further interest. For a correctly terminated line

$Z_L=Z_0 \quad Z_{IN}=Z_0$

for a short-circuit $Z_L=0$, $Z_{IN}=-jZ_0\tan\beta x$,

for an open-circuit $Z_L=\infty$, $Z_{IN}=jZ_0\cot\beta x$

and if $\beta x=\pi/2 \qquad Z_{IN}=Z_0^2/Z_L$

Electricity *and* magnetism?—2

Riding on an electron: a relativistic approach to the nature of magnetism

by "Cathode Ray"

Last month we asked whether electricity and magnetism were two separate but related things or just two faces of one thing and if so what thing. We discovered that what to one experimenter was a wholly electric field was seen (quite correctly) by another to be accompanied by a magnetic field. And vice versa. The cause of the disagreement was the fact that the observers concerned were moving relative to one another. And when, using the ordinary textbook laws of electricity and magnetism, we worked out a set of equations for converting the electric and magnetic field specifications at one position to those at another in relative motion, we found a discrepancy, which could only be eliminated by introducing into both sets of equations a factor we denoted by β (some people call it γ), equal to

$$\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

in which v is the relative velocity of motion and c the velocity of light and radio waves in space.

This was very interesting, because by a simple approach to the problem through well-known elementary Electricity we discovered the necessity for what is also the essential factor in the Lorentz transformations relating length, mass and time in Einstein's Special Theory of Relativity. This theory, implausible though it may appear, was the only escape from certain discrepancies that exist if one assumes that these basic quantities are the same for all. One of these discrepancies we found for ourselves in electro-magnetism. Another is the fact that the speed of light in space *(c)* is found to be always the same, regardless of the velocity of the measurer or of the source of the light. This seems as nonsensical as if a person trying to stand up in a racing car, and another motionless on the track, both reported identical wind velocities. But it is an experimental fact. And we have found that the factor β, which defines the effects of motion on length, mass and time, does the same for electric and magnetic fields.

Suppose we have two cathode-ray tubes side by side. The dotted lines in Fig. 4 represent the two rays or beams

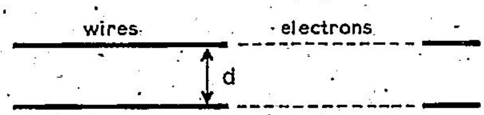


Fig. 4. The continuous and broken lines represent respectively the wire and cathode ray parts of two parallel circuits. Some curious results are obtained when the electric and magnetic forces between circuits are calculated in different ways.

consisting of streams of electrons moving from left to right. This is happening in a part of each tube between anode and screen at the same potential, so the velocity, v, of the electrons is constant. The charge on one electron is e (1.6×10^{-19} coulombs) so, if there are n electrons per metre length of beam, the current *(I)*, being the total charge passing a fixed point per second, is *nev* amps.

Now consider the wires carrying this current to the c.r. tubes. They have been laid parallel to one another at the same distance apart (*d*) as the electron beams. These wires are electrically neutral or uncharged, because for every electron there is a proton forming a fixed part of the structure of the wire. So the negative and positive charges exactly cancel out. So there is no coulomb or electric force between the wires.

The textbooks tell us, however, that because of the magnetic interaction of currents two parallel wires carrying current in the same direction will attract one another with a force equal to

$$\frac{\mu(nev)^2}{2\pi d} = \frac{\mu I^2}{2\pi d} \text{ newtons per metre of wire,} \quad (6)$$

μ being the local permeability, normally the "magnetic space constant", μ_0. Although the electrons in the beams are travelling enormously faster than those in the wires, they are much more widely spaced, and as I is obviously the same at all points in the circuit we see that *nev* is the same in both places. So the beams too will be magnetically attracted. And they would consequently deflect themselves towards one another, were it not that here there are no protons to neutralize the negative charges of the electrons. Being of like sign, the beams will repel one another, and the textbooks tell us that this force is

$$\frac{n^2e^2}{2\pi\epsilon d} \text{ newtons per metre} \quad (7)$$

ϵ being the local permittivity, normally the "electric space constant" ϵ_0. So there will be a tug-of-war between these forces.

It is easy to predict which will win. The magnetic attraction *(6)* can be arranged as

$$\frac{n^2e^2}{2\pi\epsilon_0 d}\epsilon_0\mu_0 v^2$$

So, looking again at *(7)* we see that the ratio of magnetic to electric forces is $\epsilon_0\mu_0 v^2$. We noted last month that $\epsilon_0\mu_0 = 1/c^2$, c being the speed of light, so the ratio is v^2/c^2. The electrons can never move as fast as c, so the electric repulsion always wins. Even in a high-voltage c.r. tube v is much less than c, so v^2/c^2 is a very small fraction, and the total or net force is nearly all electric.

Combining the expressions for the separate forces we see that the total force can be written as

$$\frac{n^2e^2}{2\pi\epsilon_0 d}\left(1-\frac{v^2}{c^2}\right) \quad (8)$$

If the term in brackets looks familiar it is because it is closely related to the relativity factor, β, which we have just repeated from Part 1. So yet another version of the net force per metre is

$$\frac{n^2e^2}{2\pi\epsilon_0 d}/\beta^2$$

which we can write more briefly still as

$$\frac{k}{\beta^2}$$

k being the electric part of the force. Unless $v=0$, β is always greater than 1, so we see that the net force (though positive, showing conventionally that the electric repulsion prevails over the magnetic attraction) is less than if only the electric force operated.

So here we have β turning up yet again! We originally saw it creeping into the situation where we found that what to one observer was a purely electric field was to another observer in relative motion a mixture of electric and magnetic fields. Then we noted that it was the essential factor in the Special Theory of Relativity. And now we have used textbook "Electricity and Magnetism" to find that our two electron beams acted on one another with a mixture of electric and magnetic fields and forces. But when we jumped on to an electron, so that all the electrons were (to us) standing still, there were no electric currents, so no magnetism, and the only force was what we are now calling (for short) k. Back in the lab., we were aware of the beam currents and the consequent magnetic force, kv^2/c^2.

So here we have a discrepancy between the force between the beams as measured at rest in the lab. (electric repulsion, slightly offset by magnetic attraction) and as measured by someone moving with the electrons, which to him are not a current, so magnetism doesn't enter in and the electric force is on its own.

But we have been using ordinary textbook formulae for these things, all innocent of relativity. So we naturally suspect that this discrepancy is another of those encountered when Einstein is ignored. The discovery that the discrepancy is β^2 makes the suspicion a virtual certainty. So let us take account of relativity.

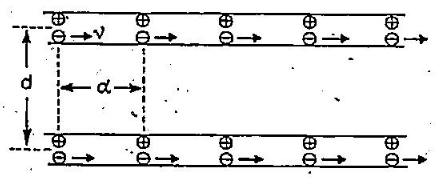


Fig. 5. This is an idealized model of the parallel wires in Fig. 4, showing the protons ⊕ and electrons ⊖.

Fig. 5 shows a sort of simplified model of the electric charges in a short section of the parallel wires. The charges are assumed to be distributed along each wire with a density n (of each kind) per metre. So the charge per metre is $\pm ne$. The protons or positive charges, being parts of the wire, are fixed. The electrons are supposed to be moving to the right with velocity v. (So the current, by convention flowing to the left, is equal to nev.) Without relativity one would say that as there are equal numbers of positive and negative charges on each wire it is electrically neutral, so there is no net electric field or force between them. But because the electrons are moving relative to the protons, we do have to take account of relativity. Let us divide the force per metre into four parts:

(a) Between the two lots of protons $(++)$

(b) Between the lower lot of protons and the upper lot of electrons $(+-)$

(c) Between the upper lot of protons and the lower lot of electrons $(-+)$

(d) Between the two lots of electrons $(--)$.

Force $(++)$ is a repulsion, so is $+k$

Force $(+-)$ is an attraction, so is $-k$

Force $(-+)$ is an attraction, so is $-k$

All these are as seen by the fixed protons, or by ourselves using suitable lab. gear.

No question can arise about $(++)$, because all the charges concerned are at rest relative to us. But what about the moving electrons; doesn't some relativity correction have to be made where they are involved? However that may be, the essential fact is that in our "frame of reference" (call it S) all the electrons pass the protons simultaneously, so they must be spaced the same distances apart, so their charge density must be the same as that of the protons and the normal calculation for k holds good. We see that the net result of all three forces (a) to (c) is $-k$.

Calculation of the last one, $(--)$, is different though. To estimate this force we have to run alongside the electrons, in their frame (S'), where they are stationary and we can apply the electric force equation quite normally, so long as we use dimensions that apply in S'. The only factor in k that is subject to relativity is n, the number of electrons per metre. (d is at right angles to the direction of motion, so is unaffected.) The rest of k, $e^2/2\pi\epsilon_0 d$, we can abbreviate for convenience to p. We shall distinguish the electric force of repulsion between the two sets of electrons in S' as f'_e, and the electron density here as n'.

It might seem reasonable to argue that as the protons in S see the moving electrons spaced the same as themselves (because the coincidences in distance also coincide in time) the electrons in S' see the (to them) backward-moving protons coinciding likewise and the spacings therefore equal. And before Einstein this argument certainly would have been unassailable. Even now most people find it obvious that if two events, such as electrons passing protons, occur exactly simultaneously (as seen, say, by someone stationed midway between the two events) they must be simultaneous, full stop. But Einstein showed that they are not simultaneous so far as anyone in relative motion is concerned. So if, having checked that when we are stationary relative to the protons the electrons coincide momentarily with them simultaneously all along the line, we transfer from S to S' by moving along with the electrons, we find that this is no longer so.

The first thing that we notice when we settle down in our new abode is that the protons are moving past with velocity $-v$. And because distances in a moving system (in this case S) are reduced by the factor $1/\beta$, according to Lorentz, the protons look closer together than they did when we were in S. And therefore there are β times more of them per metre. But that observation is really quite irrelevant, for we have done with the protons now and must concentrate exclusively on the electrons. We see these standing still, so their distances apart are not subject to Lorentz contraction. But they were so subject in S, so we can now say that in S' the distances between electrons are *de*contracted, or expanded. So there are fewer electrons per metre. Because the distances between them are β times greater than in S, the number of them per metre must be $1/\beta$ as many as in S. In symbols, $n'=n/\beta$. Fig. 6 shows a piece of one wire as it appears in S and in S'.

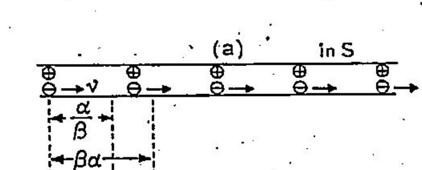


Fig. 6. In system S, in which the wires in Fig. 5 are stationary, each wire looks the same as in Fig. 5, (a). But in system S′, in which the electrons are stationary, each wire looks as at (b).

Because the electrons are standing still in S' we can use the standard equation for the repulsive force per metre between the two wires without any relativity complications. In our abbreviated form it is

$$f'_e=(n')^2p$$

Having taken that in, we get back into S. It is a principle of the theory of relativity that the laws of nature are the same in all inertial systems, which means systems that are not accelerating or decelerating. So

$$f_e=f'_e=(n')^2p=\left(\frac{n}{\beta}\right)^2p=n^2p\left(1-\frac{v^2}{c^2}\right)=k\left(1-\frac{v^2}{c^2}\right)$$

If we add this to the sum of the three forces (a) to (c), which we found to be $-k$, we get as the sum of all four forces

$$-k\frac{v^2}{c^2}, \text{ or } -\frac{\mu_0(nev)^2}{2\pi d}, \text{ or } -\frac{\mu_0 I^2}{2\pi d}$$

Being negative it is conventionally a force of attraction. In fact, this is the standard formula (6) for the magnetic force of attraction between two parallel wires spaced d metres apart and each carrying a current I in the same direction. But from the way we arrived at it, *it is a purely electrical force*, due to an inequality in the balance of positive and negative charges in the wires when *both* are carrying current and account is taken of relativity—which we found we had to take into account last month in order to make sense of our assessments of fields existing in relatively moving systems, on a basis of schoolbook Electricity.

We also noted for future attention the voice of the sceptic who declared that magnetic forces couldn't possibly be actually the *same* as electric forces because one could distinguish between them by experiment. In particular, an electrically charged droplet floating in space is attracted by an opposite electric charge, but is totally unaffected by the strongest magnetic field. We now see that this argument is fallacious. The reason the charge doesn't respond to the "magnetic" field is that it is stationary therein, so it sees an exact balance between the positive and negative electric charges in the wires energizing the magnet, even though one lot of them is in motion. But directly the droplet itself moves it is in another frame of reference and sees an inequality of charge and therefore an electric field, which deflects it from its path.

The title question, then, haanswered by the conclusion that "magnetism" can be accounted for by purely electric attraction and repulsion. Of course, this conclusion has been reached only for one simple case—parallel wires carrying equal currents in the same direction—but the principle is the main thing. The same demonstration can be very easily adapted to cover currents flowing in opposite directions, giving a force of opposite sign, repulsion. It is only a little more complicated to include unequal currents. In this case there are two different electron velocities, say v and u, and instead of v^2 in the numerator we get vu. This shows that there is no force if *either* current is zero. It is noticeably more difficult to deal with charges moving along non-parallel paths, and if you want to go into this I suggest you study "Classical Electricity via Relativity" by W. G. B. Rosser, Chap. 3 (Butterworth, 1968).

Having discharged (if that is the right word) my brief, I might now be expected to conclude the whole session and release you to read more interesting parts of this issue. But you might just find it worth while to tarry yet a few minutes while together we do some rather remarkable arithmetic.

In our Fig. 4 the current in each circuit will probably be less than 1mA, and the forces between beams and wires admittedly small. So let us take an example where the force should be quite appreciable; say 1 amp flowing in each wire having a cross-sectional area of 1mm². We know the current is equal to nev. Any book on electricity will tell us $e=1.6\times10^{-19}$ coulombs. And some books will tell us that in copper there are roughly 10^{29} movable electrons per cubic metre. In a metre of our wire the volume is 10^{-6} cubic metres, so n is 10^{23}. From $nev=1$, then, v is $1/(10^{23}\times1.6\times10^{-19})$, or about 6.3×10^{-5} metres per second, or 0.063 millimetres per second. Compared with which, a snail seems to be in a tearing hurry.

Seeing that the effects of relativity can normally be neglected even at supersonic jet speeds, can it seriously be maintained that velocities of this minute order can result in forces sufficient to drive electric motors? We found the ratio of "magnetic" to electric force between the beams to be v^2/c^2, and were it not for the charge-neutralizing effect of the protons this would apply to the wires too. The ratio of forces would be $(6.3\times10^{-5})^2/(3\times10^8)^2$, or 4.4×10^{-26}!

This figure begins to look less utterly insignificant if we take the trouble to work out the *unneutralized* electric force per metre of wire in our example. We know well by now that it is k, or $n^2e^2/2\pi\epsilon_0 d$. n is roughly 10^{23}, e is 1.6×10^{-19}, ϵ_0 is nearly 9×10^{-12}; and let us suppose d is 0.01 metre (1 cm). Then the force is 4.6×10^{20} newtons. Or 46,000,000,000,000,000 [...]ons! It is to this that the 4.4×10^{-26} [r]atio has to be applied. So the "magnetic" force turns out to be an appreciable 2×10^{-5} newtons, or 2 dynes. Which is the same as you would get by using the traditional formula for electrical attraction between parallel wires (equation 6).

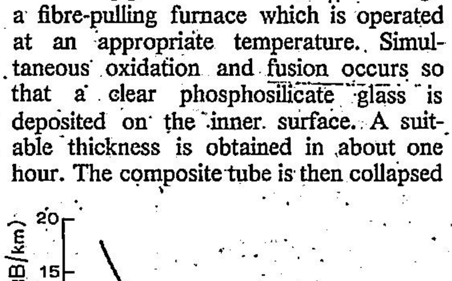
Low-loss optical fibre

Interest in the potential use of optical fibre waveguides in the telephone network, has resulted in recent dramatic reductions in fibre attenuation. There has been considerable expenditure and effort in laboratories in this country, as well as abroad, which has produced silica-based fibres with remarkably low losses of around 2dB/km. Groups at Standard Telecommunication Laboratories, Bell Telephone Laboratories and Corning Glass Works have used either germania or boric oxide to modify the properties of silica to produce an optical guiding structure.

However, a research team led by Professor W. A. Gambling at Southampton University has produced a new type of fibre with similarly low losses but based on an entirely different and unexpected material. The process by which the fibre is made is also new and has almost entirely eliminated the sharp absorption bands, associated with "water" impurity in the glass, that have affected most other fibres. This new solid-core fibre has extremely low loss over the entire wavelength range 0.4 to 1.1μm with minimum values of 2dB/km at the gallium arsenide and neodymium laser wavelengths.

The fibre has a core material comprising a phosphosilicate (P_2O_5/SiO_2) glass contained in a pure silica cladding. At first sight, this is an unlikely combination since glasses do not exist in bulk form having such a phosphosilicate composition. The big advantage is, however, that the addition of phosphorus pentoxide to silica does not increase the absorption and scattering losses as is the case with some of the additives (e.g., germania, titania) used by other workers. Further phosphorus is an abundant element, easily available and relatively cheap.

To produce the phosphosilicate glass a new technique comprising controlled chemical-vapour deposition has been devised. The starting materials are purified silicon tetra-chloride and phosphorus oxychloride, which are vaporized, mixed with oxygen and passed through a tube of silica cladding glass. The tube containing the flowing gas mixture is traversed through a fibre-pulling furnace which is operated at an appropriate temperature. Simultaneous oxidation and fusion occurs so that a clear phosphosilicate glass is deposited on the inner surface. A suitable thickness is obtained in about one hour. The composite tube is then collapsed



Spectral a[...]ation curve of 1.2km length of [...]sphosilicate-core silica cladded f[...] at Southampton Universit[...]

and drawn into a fibre using a specially-developed graphite resistance-heated furnace. Operating temperature, which can be in excess of 2,200°C, is monitored by a thermocouple to allow accurate control and repeatability. The fibres typically have a core diameter of 50μm, an overall diameter of 150μm and are drawn in lengths of about 1.2km. Numerical aperture can be varied up to 0.18 or more as desired by control of the relative concentration of phosphorus pentoxide in the core. Either a uniform, or a graded, refractive index can be provided in the core.

Even though the loss already achieved is extremely low it has been shown that the phosphosilicate core material is capable of further improvement. It is confidently expected that a transmission loss of about 1dB/km will be achieved with further purification of the starting materials.

In addition to ultra-low loss the fibres exhibit very low values of pulse dispersion and are capable of bandwidths of more than a gigahertz over lengths of 1km.

It will be recalled that two years ago the Southampton group announced a liquid-core fibre having the lowest loss (5dB/km) for any type of fibre at that time. It is still the best liquid-core fibre that has been produced anywhere and a 1km length was used to give the world's first transmission of a live colour television programme by the BBC.

Sixty Years Ago

From *Wireless World*, Oct. 1914:

The Amateur's Wish

Alas, Poldhu! thy blaring bugle note
Which oft at midnight pleased my list'ning ear;
And Clifden, too, thy mighty waves which float
Five miles apart, wide wafting signals clear,
For me are gone. My 'phones no longer sing
The music which was prompted by your sparks,
Nor can they tell, if still ye nightly fling
Abroad, meteorological remarks.
My watch ticks on, unchecked; I cannot fix
Its hands to Greenwich time, and set it right,
For Paris purring "tas" and "tuts" and "ticks"
Ne'er reach my ears. My aerial's gone from sight,
Gone Cleethorpes' mystic messages that thrill,
And turn my thoughts to men, and ships, and might.
Gone, too, Madrid, whose plaintive whistling shrill
I've heard, with straining ears, across the night.
My jigger lies, with coils and aerial-lead
In tight-packed drawer; it can no longer slide
To tune, helped in its work, to let me read
Far signals, by condensers on each side.
Shall I complain? No, never! From it far,
Such hobbies now must all aside be laid
Since I have heard the "ta-te-ta-te-ta"
My country sent to call me to her aid.
And so instead I'm tuning up a gun,
And learning how to shoot, to march, and wait
With hope, to help in things which can be done
By those who turn to drilling rather late.
And if I'm called away to leave my home,
Should I, before I go, just take a peep
To see that all within my wireless room
Is right, I know this thought will on me creep.
"When peace again doth reign, and war is done,
God grant my 'phones may sing of victory
In notes that spell the words of England's tongue,
Sent out by British hands on Norddeich key."

Aylmer A. Liardet.

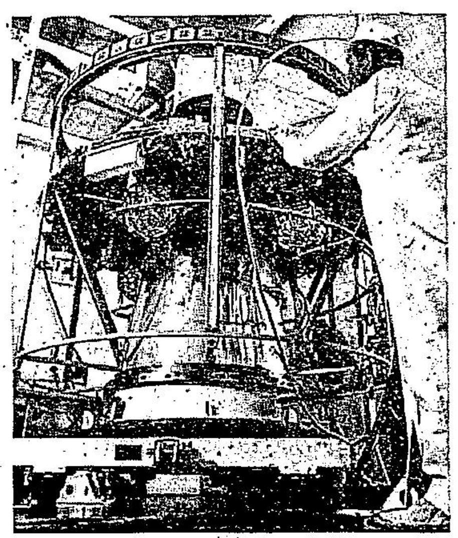
British satellite launch

The second model of Britain's Skynet II, the first operational communications satellite to be built outside the USA or Russia is due for launch from Cape Canaveral in November by a Thor-Delta rocket. Coupled with this in Britain's space achievements is the scheduled launch of UK 5, the latest scientific satellite in the collaborative programme with NASA. This advanced X-ray satellite carries experiments provided by British and American researchers, and is designed to carry out the most comprehensive investigation yet initiated into X-ray sources in deep space including phenomena which might explain the existence of "black holes" in space.

Skynet II. This satellite will carry British defence communications over an area from the UK to the Far East. It will replace the smaller, US-designed and built Skynet I satellites. Skynet II is built in the form of a cylindrical drum with solar cells covering the entire curved surface. It measures approximately 78in long with a diameter of 75in. Launch weight is about 960lb.

Transfer of the satellite from its original highly elliptical orbit into synchronous orbit will be achieved by firing a solid fuel apogee motor contained in the satellite. The complete satellite will be spin-stabilized at about 90 revolutions per minute from the time second-stage burning ceases. However, once in synchronous orbit the communications antenna will be de-spun and controlled to point constantly at the Earth.

During the initial manoeuvres and up to the time of its final positioning, the satellite will be controlled through an almost omnidirectional aerial system consisting of an array of cavity-backed dipoles operating at S-band and mounted in a single strip around the complete circumference of the satellite. Once the synchronous orbit has been achieved and the satellite has been turned into the correct position related to the Earth, a single horn antenna mounted on the spinning axis of the satellite can be brought into use to provide the main communications function of the satellite. This antenna, whose beamwidth is sufficient to cover the entire visible portion of the Earth's surface, will be mechanically de-spun and aimed at the Earth's centre. The S-band multi-dipole aerial will then be used to monitor all the functions of the spacecraft and to transmit commands to it.



Skynet II undergoing check-out at the Marconi Space and Defence Systems' Portsmouth spacecraft factory.

UK 5. This all-British satellite was scheduled for launch by a US "Scout" rocket from an oil-rig-type platform situated three miles off the coast of Kenya. It is the first British satellite to carry a core store system for processing experimental data before it is transmitted to the ground and will also be the first British scientific satellite to use pulse code modulation for the telemetry link. UK 5 will carry a scientific payload of six X-ray experiments into a near equatorial orbit and should remain operational for at least one year. The experiments on board the satellite are designed to locate cosmic X-ray sources, including pulsars, and to measure their spectra, period, variation and polarization. The experiments are as follows: measurement of X-ray source positions and a sky survey in the energy range 0.3 to 30keV, University College London; sky survey in the range 1.5 to 20keV, University of Leicester; study of the spectra of individual sources in the 2 to 30keV range, Mullard; measurement of the polarization of X-rays from 1.5 to 8keV, University of Leicester; study of sources of high energy X-rays up to 2MeV, Imperial College, London; an all sky monitor in the energy range 3 to 6keV, Goddard Space Flight Centre.

The results of the six experiments will be fed in digital form through an interface unit into a data storage system. This will store the information gathered during each orbit and then transmit it to the ground as the satellite passes overhead the receiving network. Commands will be transmitted from the ground providing instructions to the spacecraft and its experiments for data collection in the next orbit.

Skynet II was designed [illegible]ilt for the Ministry of Defence by M[illegible]pace and Defence Systems Ltd[illegible]so prime contractors for U[illegible]

Supernova probe

The United States and Great Britain are to undertake a joint rocket mission next June to aim an X-ray telescope at the remnants of a distant supernova. The project calls for the launch of a British Skylark sounding rocket from the Woomera Rocket Range in Australia towards the Puppis A supernova remnant, an object of intensive study for several years.

A supernova can originate in a large star at the end of its life when the final collapse is a cataclysmic event that generates a violent explosion, blowing the innards of the star out into space. There the material mixes with the primeval hydrogen of the universe. Later in the history of the galaxy, new stars can be formed from this mixture. Consequently, the study of remnants of exploded stars such as Puppis A could provide important information on the evolution of stars and galaxies.

A Wolter type 1 glancing incidence X-ray telescope designed and built by NASA will be used in conjunction with a high resolution position sensitive detector invented and developed by the Mullard group. The combination will permit structural details of the regions responsible for soft X-ray emission of Puppis A to be studied with high resolution.

Puppis A, the subject of previous study by sounding rockets and the Copernicus (OAO-3) satellite has been found to be one of the brightest soft X-ray sources in the sky. Telemetered data from the Skylark experiment will provide two-dimensional images of the X-ray-emitting regions of Puppis A which can be compared with previous observations to develop more precise models of the supernova phenomenon.

More about Apollo-Soyuz

The joint space-venture between the USA and Russia which involves the in-orbit docking of the Apollo command module with a Soyuz spacecraft is planned for launch on July 15, 1975 (see Space News, August 1974, p.287). During the mission, the crew will conduct important new technological and medical experiments. Atmospheric experiments will be conducted using a new technique for measuring constituents which are too chemically reactive to measure directly with a mass spectrometer. This will be accomplished by sending an optical signal from the command service module to a reflector on the Soyuz vehicle. The signal will be bounced back and scanned in the Apollo spacecraft to study the effects of the sun on atomic oxygen and nitrogen at orbital altitudes. Also included is an experiment in electrophoresis processing. An electric field is used to separate living cells and other biological materials from a flowing medium without decreasing their activity in near zero gravity conditions. Successful demonstration by the Apollo-Soyuz test proje[illegible] could lead to further development of space electrophoresis in shuttle missions, as a tool for medical research and therapy and contribute to such fields as immunology and cancer research.