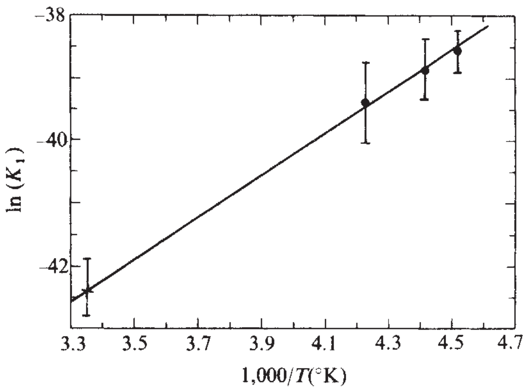

Fig. 2 A $\ln(K_1)$ plotted against $1{,}000/T$. The point marked X is from an analysis of the experimental data of Wongdontri-Stuper *et al.* Remaining data points (●) are from an analysis of stratospheric measurements as explained in the text. The straight line represents a least square fit to the data points.

Wongdontri-Stuper *et al.* arises from the uncertainty in the rate coefficient of the overall reaction of $ClO{\cdot}O_2$ with ClO. The error bar attached to this $\ln K_1$ reflects an arbitrary, but reasonable, conjecture that the abovementioned rate coefficient may be either a factor of two larger or smaller than the nominal value used previously[1]. A least square analysis yields $K_1(T) = 3.28\times10^{-24}\exp(3{,}470/T)$ cm^3 molecule^{-1}, with $K_1(T) = 7.28\times10^{-24}\exp(3{,}464/T)$ and $1.16\times10^{-24}\exp(3{,}549/T)$ cm^3 molecule^{-1} as the upper and lower bounds. The main points are: (1) K_1 obtained from two entirely independent considerations—analysis of laboratory data and stratospheric measurements—lie very close on a single plot, and (2) the slope of this ln K against $1/T$ plot is as expected by analogy with other loosely bound species, such as ClOO. These are not unlikely to be chance coincidences. These two points suggest that the possible existence of $ClO{\cdot}O_2$ complex in laboratory experimental situations can be extrapolated to a possible existence of $ClO{\cdot}O_2$ in the stratosphere; in quantities sufficient to resolve the current discrepancy between the measurements of Anderson *et al.*[5,6] and current theoretical models of stratospheric ClO mixing ratios.

As pointed out by Logan *et al.*[7], "The observed variability of ClO is puzzling, and raises the possibility of a major gap in our description of the chlorine cycle". Our conjecture is that the potential existence of $ClO{\cdot}O_2$ in the stratosphere bridges this gap. We have already seen how $ClO{\cdot}O_2$ complex may possibly explain the current discrepancy between observed and theoretically predicted altitude profiles of the ClO mixing ratio. Rocket measurements[9] of stratospheric T and n indicate that local changes in these quantities tend to reinforce each other's effect on the ratio $n(ClO{\cdot}O_2)/n(ClO)$ via equation (10), and a day-to-day variability of this ratio by as much as 50–60% is quite possible even at 30 km from this cause alone. Thus, the introduction of $ClO{\cdot}O_2$ could make the observed variability of ClO more understandable. In addition, it is possible that the reaction:

$$ClO{\cdot}O_2 + O \rightarrow OClO + O_2 \qquad (3b)$$

occurs. Photodissociation of OClO, that is, $OClO + h\nu \rightarrow O + ClO$, results in regeneration of odd oxygen. The fraction of $ClO{\cdot}O_2$ which reacts with O via reaction (3b) to produce OClO does not immediately destroy odd oxygen. Consequently, $ClO{\cdot}O_2$ in the stratosphere and reaction (3b) together may have a mitigating influence on the present estimates of ozone reduction due to chlorofluoromethane consumption. Finally, a direct experimental verification of possible $ClO{\cdot}O_2$ formation from ClO and O_2 would be very useful.

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Observation of static electromagnetic angular momentum *in vacuo*

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Our programme of measurement of forces related to electromagnetic momentum at low frequencies in matter has culminated in the first direct observation of free electromagnetic angular momentum created by quasistatic and independent electromagnetic fields E and B in the vacuum gap of a cylindrical capacitor. A resonant suspension is used to detect its motion. The observed changes in angular momentum agree with the classical theory within the error of ~20%. This implies that the vacuum is the seat of something in motion whenever static fields are set up with non-vanishing Poynting vector, as Maxwell and Poynting foresaw.

In establishing the electromagnetic nature of light, Maxwell[1] opposed Weber's "action at a distance" with his "dynamical" model of a vacuum with hidden matter in motion. His ideas were expanded by Poynting through the energy-flux theorem, but relativity theory initially dealt them a blow. However, despite Einstein's explicit reconciliation with the aether[2] there is currently some doubt about Maxwell's medium. It was in a relativistic context that Minkowski[3] found, as a purely mathematical consequence of Maxwell's equations, that the Lorentz force density could be exactly expressed as the divergence of Maxwell's tensor *in vacuo*, T_{vac}, decreased by the rate of change of Poynting's vector:

$$\rho\mathbf{E} + \mu_0\mathbf{J}\times\mathbf{H} = \nabla\cdot T_{\text{vac}} - \frac{\partial}{\partial t}\varepsilon_0\mu_0\mathbf{E}\times\mathbf{H} \qquad (1)$$

According to Maxwell–Poynting ideas, the last (Minkowski's) term in equation (1) can be interpreted as a local reaction force acting on charges and currents when the vacuum surrounding them is loaded with electromagnetic momentum. Einstein and Laub[4] observed that if equation (1) is integrated to all space, the term $\nabla\cdot T_{\text{vac}}$ generates a vanishing surface integral and therefore the system of all Lorentz forces in the Universe needs to be supplemented with the quantity $\int_\infty \varepsilon_0\mu_0\,\partial/\partial t\,\mathbf{E}\times\mathbf{H}\,dv$ to preserve Newton's third law. The opposite of this last vector is usually interpreted as the net unlocalized reaction on charges and currents due to radiation fields but, classically at least, it also represents a real reaction force even with induction fields.

We have made, to our knowledge, the first direct observation of the Minkowski term with induction fields **E** and **B**, which are confined to a small volume so that the local nature of the vacuum reaction term has also been demonstrated. The experiment consists of measurement of the axial torque on a cylindrical capacitor and its radial leads, located in an axial magnetic field. Thus $\mathbf{E}\times\mathbf{H}$ is azimuthal inside the vacuum gap of the capacitor. The details of the capacitor and its mounting on a torsion oscillator are shown in Fig. 1. The capacitor and its leads form a rigid and nearly closed electrical loop. The magnetic field and the capacitor voltage are time varied so that one Fourier component of their product is locked to the resonant frequency

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of the mechanical system, which is of sufficiently high $Q(>10^5)$ to yield a measurable oscillation amplitude when viewed by a μ-radian sensitive optical lever. Knowledge of the resonant amplitude and frequency, moment of inertia and free decay time (with $\mathbf{E}=0$) yield the driving torque. The suspension system is located in the vacuum interspace of a liquid helium Dewar. The magnetic field, uniform to ~2%, is supplied by a superconducting solenoid.

This technique is an extension of our previous work[5] on electromagnetic forces in material media, with dielectric or magnetic material in the capacitor. In those experiments, the magnetic field was held fixed and the voltage was impressed at the resonant frequency. This resulted in a large resonant noise due to elestrostatic forces (at the second harmonic) which coupled back in some degree at the resonant frequency. The present experiment was made possible by detuning the voltage from resonance by ~1 Hz, using as a source the output of a high stability oscillator. This signal ($\nu = 243.31$ Hz) was electronically multiplied by the signal ($\nu = 242.18$ Hz) from the slave oscillator phase locked to the resonant system by the optical lever, so that sum and difference frequencies were generated. After low pass filtering, the difference signal was used to drive the magnet. In this way, one component of the product $\mathbf{EH}$ was at the resonance but $(\mathbf{E}^2)^{1/2}$ was not. The various phase shifts in the circuitry were carefully nulled. A calibrated pick-up coil provided absolute measurement of $\mathbf{H}$. The apparatus permitted reasonable measurements of torque over a range of about a factor of 3 in both $\mathbf{E}$ and $\mu_0\mathbf{H}$, up to maximum amplitudes of 2×10^6 V m^{-1} and 0.3 T respectively.

Measured torques are compared in Table 1 with calculated torques acting on the suspension which arise entirely from the net Lorentz force on the current $\mathbf{I}$ in the radial leads which charges the vacuum component of the suspended capacitor, that is, a torque $I\mu_0H(a^2-b^2)/2$, where a and b are the outer and inner radii of the capacitor cylinders (~5.5 and 4.5 mm). Here I has been corrected for the known stray capacitance to earth

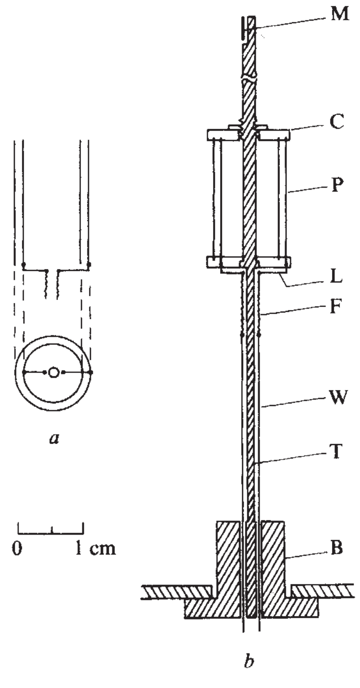

Fig. 1 (*a*). Scale views of the capacitor and its rigid leads. The capacitor is formed from two stainless steel cylinders, the rigid leads run radially to the electrodes from near the axis, where they are fixed to 0.03 mm copper fibres. (*b*), The capacitor clamped to the suspension system with polyurethane end plates (the clamping details are schematic only). M, Mirror for optical lever; C, end plates; P, capacitor electrodes; L, radial leads; F, fibres; W, stiff feed wires; T, torsion shaft; B base.

Table 1 Calculated and observed torque amplitude for typical field amplitudes (the electric field is given at the inner electrode)

E_0 (MV m^{-1})	B_0 (T)	$T_{0,calc}$ (pN m)	$T_{0,obs}$ (pN m)
0.58	0.13	2.0	1.8
0.64	0.22	3.5	4.4
1.3	0.22	7.1	8.5
1.7	0.19	7.9	8.7
2.3	0.22	12.4	17.0

external to the suspension (~1 pF effective) and for the fraction of conduction current which corresponds to polarization current in the dielectric end plates, as that part corresponds to a closed loop of current contributing no torque. Thus I corresponds to charging a pure vacuum capacitance C_0 only. C_0 was calculated from the geometry (4.7 pF) and also estimated by measuring the effect of removing one end plate (4.9 pF). The error in the calculated torque is mainly due to the uncertainty in the corrections for stray capacitance. It is estimated to be ~10%. The systematic trend in the ratio of T_{calc} to T_{obs} can be understood in terms of a small, amplitude dependent, non-linearity in the equation of motion, due to magnetic field dependence of the damping, which results in imperfect cancellation of the resonant noise[5] at high fields. Consequently, the tabulated discrepancies are within an estimated total error of ~20%.

Although this result is to be expected by classical electromagnetism, it leads inexorably to the acceptance of the physical reality of the Poynting vector, even though $\mathbf{E}$ and $\mathbf{H}$ arise from independent sources. This can be seen by seeking the system on which the third law reaction torque must act. It can be neither the external electrical circuit, as the loop is essentially closed within the suspension, nor in the magnet, which, as a coil, cannot receive an axial torque (force parallel to its own current). For angular momentum conservation, the loop is an isolated system and the reaction torque can only be considered as a change in electromagnetic angular momentum carried by the fields themselves in the region of their co-existence, that is, within the vacuum gap of the capacitor. As $I = C_0\mathrm{d}V/\mathrm{d}t$, the calculated torque is exactly equal to the volume integral of $\mathbf{r}\times\partial(\mathbf{E}\times\mathbf{H})/\partial tc^2$, so that the complete reaction is accounted for by the assignment of a real angular momentum density to $\mathbf{r}\times(\mathbf{E}\times\mathbf{H})c^2$ (ref. 5).

It is remarkable that no known 'particle' can be identified as the agent of the observed electromagnetic angular momentum in exchange with the mechanical detector. However, this does not imply that a new entity has to be introduced, because the concept of energy-momentum carried by macroscopically quasistatic electromagnetic field is already contained in Maxwell's equations. According to these, and as directly implied by our experimental result, permanent magnets and electrets can be used to build a flywheel of electromagnetic energy steadily flowing in circles in the vacuum gap of a capacitor as if Maxwell's medium were endowed with a property corresponding to superfluidity. The certainly new insight is that the quasistatic Maxwell's field is not merely an unobservable medium of interaction between matter and matter: it has in fact the mechanical properties postulated by Maxwell, in contradistinction to any "action at a distance" theory.

This experiment is continuing and a complete report will be published elsewhere.

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