Mars Magnetometry from a Tumbleweed Rover

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Abstract—The magnetic stripes on Mars defy present understanding, owing to the limited resolution of measurements from orbit. A simple magnetometer mounted on a surface vehicle capable of making wide traverses would be able to resolve the small-scale structure of these magnetic anomalies. A 'Tumbleweed Rover' a lightweight wind-blown ball, would be an ideal platform for such a measurement, which would also provide useful information on the rolling dynamics of the vehicle. We describe early field tests showing the utility of a magnetometer on such a platform.

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1. MARS MAGNETISM

Early measurements indicated that Mars lacked a significant magnetic field. However, measurements from the relatively low altitude aerobraking phase of the Mars Global Surveyor mission indicated surprisingly strong magnetic anomalies in the Southern hemisphere [1,2,3]. These anomalies appeared from orbital altitude as stripes, up to 2000km long.

At present, the nature of these anomalies (e.g. whether they are deep blocks of weakly-magnetized material, or shallow deposits of more strongly-magnetized rocks) cannot be determined, since the higher-order terms of the magnetic field are more strongly attenuated with distance (equivalently, the field sensed at higher altitudes is an average of the contributions from a wider volume). Thus the available data cannot discriminate between different models.

It therefore follows that the origin of the anomalies - perhaps as intruded magmatic dikes freezing in a primordial magnetic field- cannot be stated with certainty.

The magnetic history of Mars is also of astrobiological interest, for two reasons. First, the evolution of Mars atmosphere may have been sensitive to the presence of a strong field which would have modified (reduced) the atmospheric loss due to sputtering by the solar wind. An early magnetic field would thus have been favourable for the maintenance of a thick atmosphere and thus warm conditions for a longer period.

Secondly, the most robust evidence in the Mars meteorite ALH84001 for life is the presence of well-formed magnetite crystals which resemble those found in magnetotactic bacteria (e.g. [4]) . On Earth, these flagellate bacteria use the magnetic field to determine up and down in muddy waters, so that they can swim towards or away from the water-atmosphere interface. If there was indeed life on Mars, and if - as the crystals suggest - it was magnetotactic, it follows that the field present was useful in strength and orientation for the organisms that exploited it.

The anomalies are remarkably strong – scaled to 400km altitude, the anomalies (figure 1) are around 100nT, perhaps 10 times what terrestrial anomalies might reach. At the lowest ~100km altitudes sampled during the short aerobraking phase of the MGS mission, the actual field perturbations sensed were ~ 1500nT . When propagated to the surface of Mars, these anomalies would have strengths comparable with the ~40,000nT strength of the Earth's dipole field!

These remarkable features beg closer inspection, to determine their nature and origin, and to discover smaller-scale anomalies that are at present invisible.

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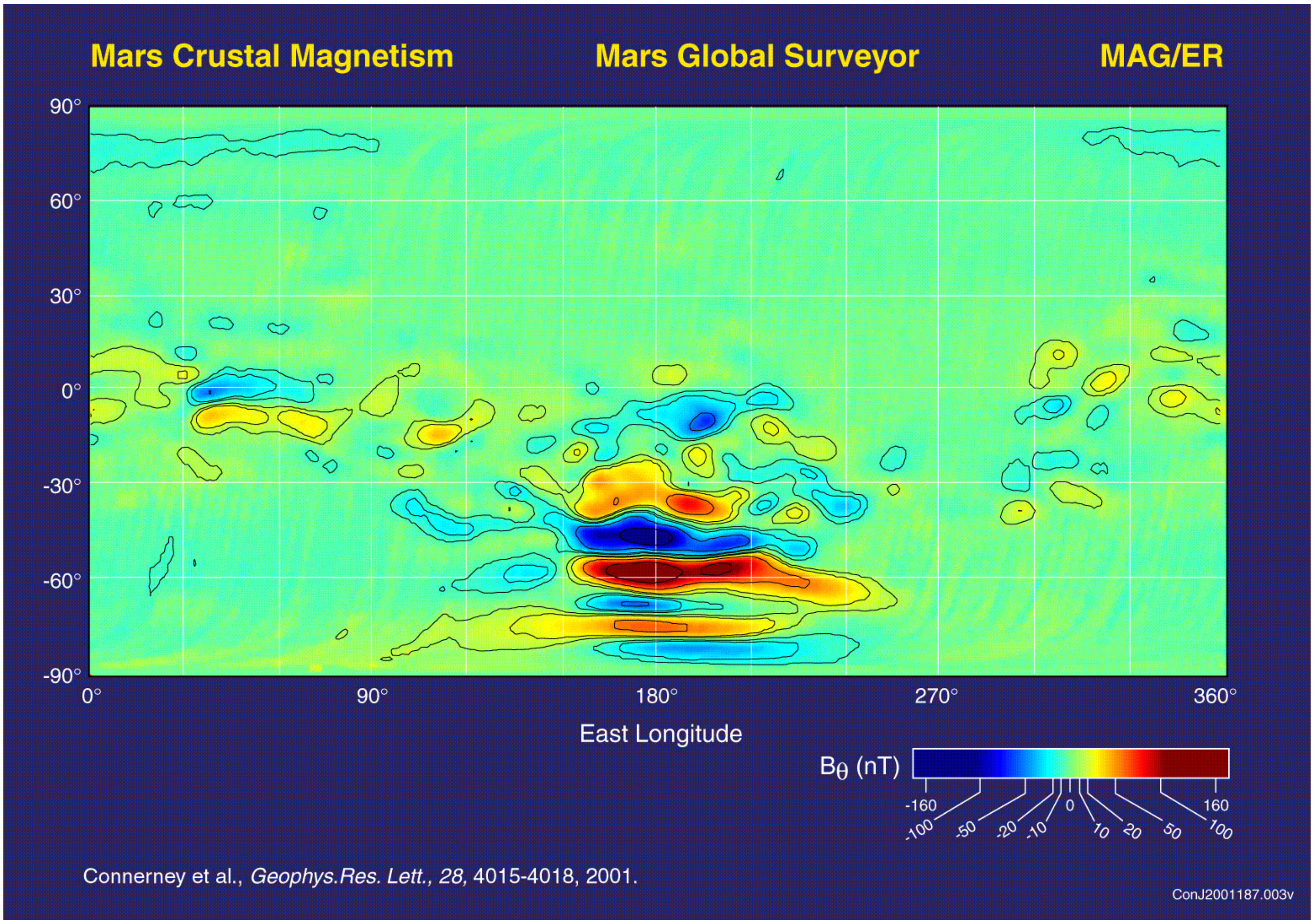


Figure 1 (from [3]) Strong magnetic anomalies have been detected in the Southern highlands of Mars. Anomalies that are weaker, and of much smaller horizontal extent, are invisible from orbit, but are likely to be abundant, and could be measured with near-surface measurements such as those from a tumbleweed rover.

2. TUMBLEWEED ROVER

The Tumbleweed Rover [5] is a mobility concept originated at JPL primarily for Mars application. It fundamentally comprises an inflatable ball with an instrumentation package mounted at the center. The vehicle derives its locomotive power simply from wind forces on its large cross-section.

In addition to providing locomotion across the surface, the vehicle is in effect its own airbag (see, e.g. [6]) , so the mass overhead associated with entry, descent and landing can be much smaller than for conventional landers. In tests in the 1960's impact speeds of as high as 60 m/s were tested with payload fractions as high as 70% : the nominal tumbleweed ball (6m diameter, 20kg ball with a 20kg payload) anticipated for Mars would have an impact speed of 30 m/s and a payload fraction of 50%.

A large effective wheel diameter ensures the vehicle is easily able to clear rocks which would present a hazard to conventional landers and rovers. The vehicle would be easily able to climb 20 degree hills and would travel at around 10 m/sec in winds of 20 m/sec.

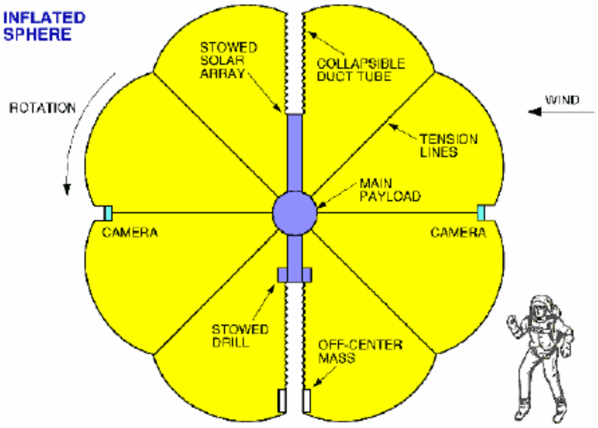


Fig 2. Tumbleweed rover schematic (from [4]), showing vehicle size for Mars application.

The rover is made from a durable fabric and may have studs, cleats or a belt 'tread' added for enhanced ground traction or to minimize abrasion of the fabric (see figure 3.)

Fig.3 Field test at El Mirage dry lake bed in California of a small-scale tumbleweed rover. Note mesh belt around preferred axis of rotation.

Among payloads that might be considered on a tumbleweed rover are magnetometers, cameras (nominally pointing along the axis of rotation) and meteorological sensors.

3. SENSOR DESIGN

Given the very large fields present at the Martian surface, as inferred from the MGS data, the instrumentation need not be particularly sensitive, and thus simple fluxgate or magnetostrictive sensors will be adequate. These devices are now mass-produced for applications including vehicle and wristwatch compasses, and orientation sensing for mobile robotics and computer gaming. The mass of an individual sensor now approaches 1 gram and thus the resource requirements are extremely modest.

For convenience the sensors used in the field test are single-axis fluxgate sensors, manufactured by Speake and Co of the United Kingdom. These devices (FGM-1) are simply fed a 5V current and deliver a digital pulse train whose period is proportional to the field along the sensitive axis. (Most 3-axis packages used on spacecraft are simply sets of 3 single axis sensors. One can in principle sense field orientation, e.g. with a compass needle, but this loses field strength information. Similarly scalar magnetometers give field strength – useful for finding anomalies but providing no information on vehicle orientation.)

The three sensors were mounted orthogonally in a 51mm Aluminium cube. Each device is a cylinder 8mm in diameter, 35mm long weighing 3.5g each. The block was attached, together with a commercial tilt sensor, in a diecast aluminium box that contained signal conditioning electronics, the power supply and the data acquisition system.

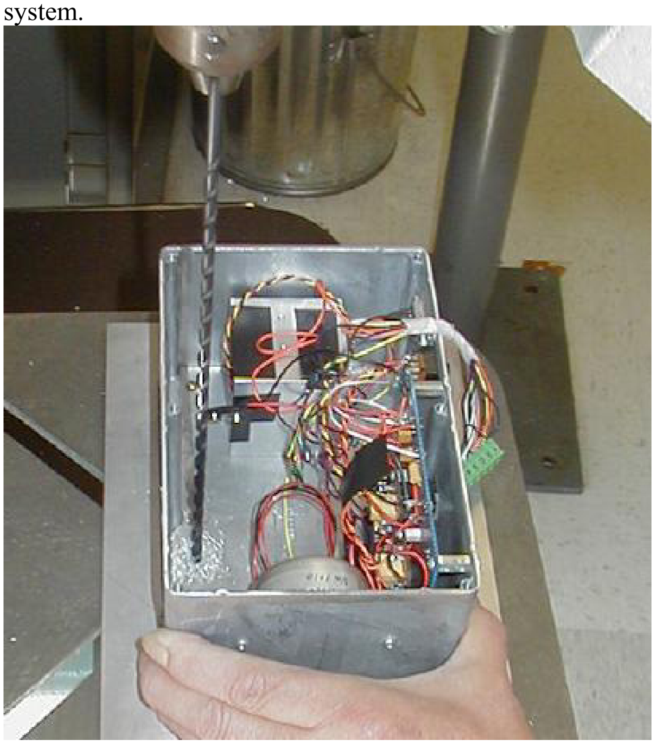


Fig.4 Last-minute adjustments (hole for securing batteries) to sensor box. Aluminium cube with magnetometers at back : cylindrical tilt sensor at front ; signal conditioning electronics to the right. The box was mounted such that the preferred axis of rotation was sensed by the tilt sensor, i.e. rotation out of page to the right.

The data acquisition system was a Pace Scientific XR440-M datalogger, a convenient self-contained unit (156g, 120x61x24mm) able to record 4 channels of analog signals with 12 bit digitization. At the 10 Hz sample rate, the unit (with a 86,016 sample memory) can record for about 40 minutes.

The signal conditioning electronics comprised for each channel a crude frequency-to-voltage converter using a diode pump – each digital pulse received dumps an RC-determined charge into a capacitor which has a resistive leak: the steady-state voltage on the capacitor is thus proportional to the pulse frequency. Other design solutions are of course possible.

The power supply was simply a set of AA cells providing 9V, regulated to 5V for the sensors, which consume, together with the signal conditioning, around 20mA each. Three of the data acquisition system's channels were fed the magnetometer outputs. The remaining channel was connected to a Spectrotilt(tm) single axis analog inclinometer, made by Spectron. This unit (a hermetically sealed 47mm diameter aluminium housing, 26mm high weighing 80g) incorporates signal conditioning and provides a DC output voltage proportional to angle, with a nominal sensitivity of 60 mV/degree.

In a real implementation of this system, a physically much smaller tilt sensor would be used (perhaps using micromachined silicon accelerometers rather than a fluid), and a microcontroller would digitally record the magnetometer output directly (e.g. by counting the time for 100 pulses from the magnetometer.) This is of course both more accurate and simpler than the quick-and-dirty setup used in the test, where an otherwise unnecessary analog step in the data chain was required to avoid a custom data acquisition build.

Fig 5. The sensor box was mounted in a central plastic/wood tube (Note the use of nonmagnetic materials!) which was the preferred axis of rotation for the rover. The tube is attached to the fabric of the rover itself via 12 tension cords.

It seems entirely probable that (assuming direct digital interfacing to the spacecraft computer is possible – modern monolithic accelerometers tend to have digital interfaces too) the 3-axis accelerometer and 3-axis magnetometer package could be installed with a mass of as little as 20g.

Clearly a modest increase in mass would permit higher performance: one obvious concept to be explored would be rather than using a more sensitive magnetometer to instead mount several simple devices on the rover, perhaps on the perimeter. This would enable the gradient of the magnetic field to be determined, providing important information on the scale of and distance to the magnetic anomaly. Since the Martian surface may well have many meteorites on its surface, some of which may be largely metallic iron, the prospect of meter-scale magnetic anomalies is likely and could be characterized by this technique. Higher sensitivity may lead to detectable influence of vehicle systems and operations (e.g. solar array currents) which could be interpreted as a good or a bad thing. While magnetic cleanliness is of course an issue that merits consideration, for vehicle dynamics measurements, the vehicle's field only provides a constant offset which is easily compensated.

Figure 6. The 6-foot diameter tumbleweed rover used in the magnetometer test at the Arroyo Seco park in Pasadena, California (near the Jet Propulsion Laboratory)

4. FIELD TEST

Although the Tumbleweed rover has been demonstrated and its performance studied in a number of field tests , at the time of writing only one small-scale field test has been conducted of the magnetometer package integrated in the rover. This was performed in late September 2001 in the Arroyo near the Jet Propulsion Laboratory, with the vehicle being rolled by hand.

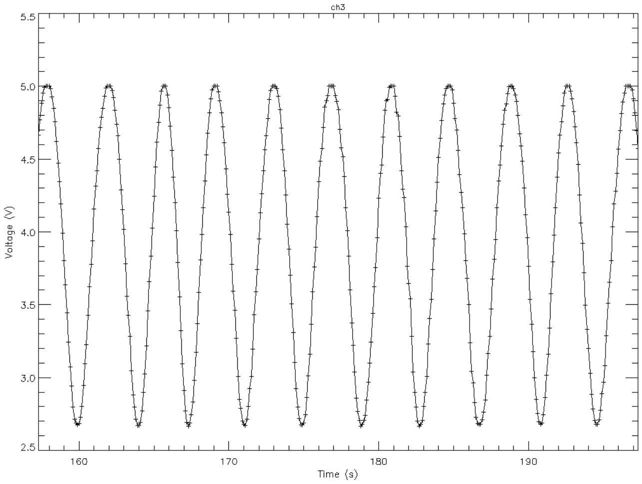


Fig. 7 Raw magnetometer signal from sensor sensitive to an axis orthogonal to that of rotation. Plus signs mark

individual datapoints (10 samples/s) . The data here show a constant roll rate of 0.25 revolutions per second, or about 3 m/s.

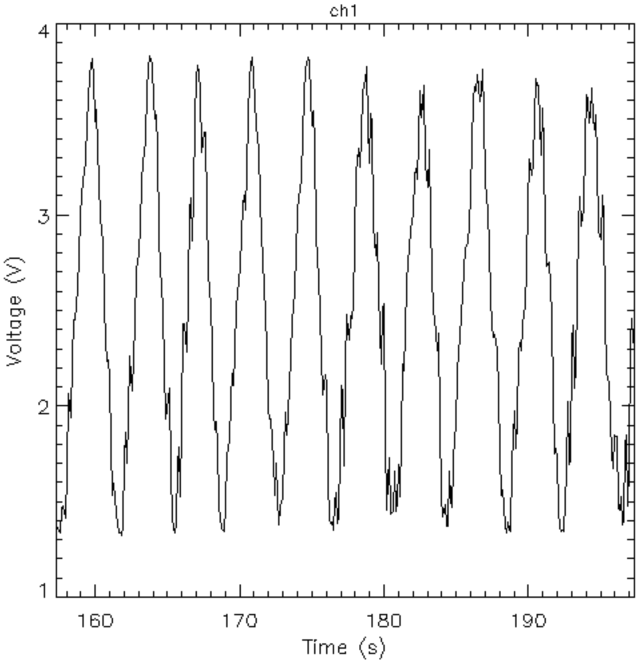


Figure 8. The electrolytic tilt sensor (channel 1) shows spurious ‘noise’ probably relating to inertial accelerations and/or sloshing response in the sensor (although it was not driven with its optimum excitation voltage) – the magnetometer (channel 3) provides a much cleaner signal.

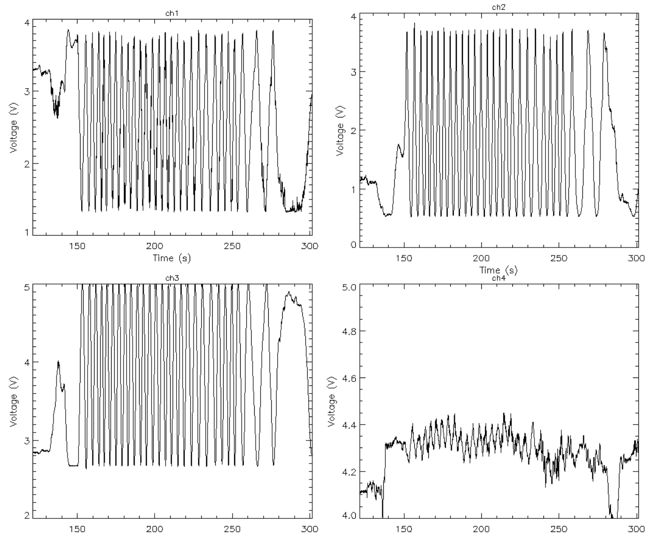
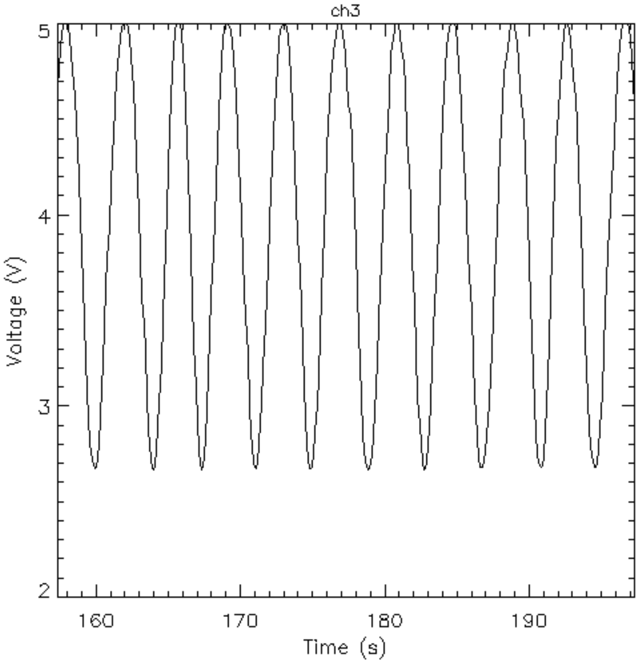


Fig. 9. The vehicle made 30 revolutions, corresponding to a traverse of 322m in 2 minutes. Note the phase difference between orthogonal magnetometers on channels 2 and 3, and the slight nonlinearity of channel 2. Channel 4 was set up with a degraded sensitivity and the data is of low quality, although the rolling signature is nonetheless quite clear.

Surprisingly, the magnetometer signature of rolling is rather cleaner than that provided by the liquid tilt sensor - perhaps due to resonance effects or sloshing in that device. It is possible that other designs might perform better.



A clean sinusoidal signal with a period of 4s is evident in all channels. This shows that the vehicle was rolling at a rate of 3 m/s.

5. DISCUSSION

The combination of accelerometer and magnetometer is expected to be useful for resolving attitude ambiguities and improving reconstruction of the vehicle kinematics. In particular, in strong winds when the vehicle can lose contact with the ground and begin tumbling and bouncing, rather than simply rolling, magnetometers alone would not provide a good estimate of the vehicle motion.

Independent attitude knowledge, which could be provided by accelerometers and sun sensors, would be useful to determine the orientation of the magnetic field vector relative to aerographic north and vertical.

We may note that while the Martian atmosphere is thin, the near-surface windspeeds are high compared with the Earth – see (e.g. [8]) Although a Tumbleweed rover may accelerate more slowly on Mars, it may typically travel faster there.

6. CONCLUSIONS

Simple magnetometer measurements from a mobile platform on or near the Martian surface show promise for an excellent scientific return with very modest resource costs. On a Tumbleweed rover, a 3-axis magnetometer package also provides useful documentation of the vehicle's motion, which in turn provides information on near-surface winds.

7. ACKNOWLEDGEMENTS

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REFERENCES

[1] Connerney, J. E. P., M. H. Acuña, P. Wasilewski, N. F. Ness, H. Rème, C. Mazelle, D. Vignes, R. P. Lin, D. Mitchell, and P. Cloutier, Magnetic Lineations in the Ancient Crust of Mars, Science, Volume 284, Issue 5415, pp. 794-798, April 1999.

[2] Acuña, M. H., J. E. P. Connerney, N. F. Ness, R. P. Lin, D. Mitchell, C. W. Carlson, J. McFadden, K. A. Anderson, H. Rème, C. Mazelle, D. Vignes, P. Wasilewski, and P. Cloutier, Global Distribution of Crustal Magnetism Discovered by the Mars Global Surveyor MAG/ER Experiment, Science, Volume 284, Issue 5415, pp. 790-793, April 1999.

[3] Connerney, J. E. P., M. H. Acuña, P. J. Wasilewski, G. Kletetschka, N. F. Ness, H. Rème, R. P. Lin, and D. L. Mitchell, TheGlobal Magnetic Field of Mars and Implications for Crustal Evolution, Geophysical Research Letters, Volume 28, Issue 21, pp. 4015-4018, 1 November 2001.

[4] R. D. Lorenz, Mars Attracts, *New Scientist*, pp.38-40 May 2001

[5] Jack A. Jones, Inflatable Robotics for Planetary Applications, 6th International Symposium on Artifical Intelligence, Robotics and Automation in Space I-SAIRAS, Montreal, Canada, June 19-21, 2001.

[6] R G Ross Jr and W E Layman, The Design and Testing of an Inflated Sphere Impact Limiter, JPL Technical Report No. 32-1037

[7] H R Everett, Sensors for Mobile Robots, Theory and Application, A K Peters Ltd., Natick, Mass. 1995, 528pp.

[8] R D Lorenz, Martian Surface Windspeeds, described by the Weibull distribution', *Journal of Spacecraft and Rockets,* vol. 33, pp.754-756, 1996

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