Magnetometry with mesospheric sodium

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Edited by William Happer, Princeton University, Princeton, NJ, and approved December 30, 2010 (received for review September 16, 2010)

Measurement of magnetic fields on the few 100-km length scale is significant for many geophysical applications including mapping of crustal magnetism and ocean circulation measurements, yet available techniques for such measurements are very expensive or of limited accuracy. We propose a method for remote detection of magnetic fields using the naturally occurring atomic sodium-rich layer in the mesosphere and existing high-power lasers developed for laser guide star applications. The proposed method offers a dramatic reduction in cost and opens the way to large-scale, parallel magnetic mapping and monitoring for atmospheric science, navigation, and geophysics.

atomic physics | geomagnetism | optical pumping

Measurements of geomagnetic fields are an important tool for peering into the Earth's interior, with measurements at differing spatial scales giving information about sources at corresponding depths. Mapping of fields on the few meter scale can locate buried ferromagnetic objects (e.g., unexploded ordnance or abandoned vessels containing toxic waste), whereas maps of magnetic fields on the kilometer scale are used to locate geological formations promising for mineral or oil extraction. On the largest scale, the Earth's dipole field gives information about the geodynamo at depths of several thousand kilometers. Magnetic-field variations at intermediate length scales, in the range of several tens to several hundreds of kilometers likewise offer a window into important scientific phenomena, including the behavior of the outer mantle, the solar quiet dynamo in the ionosphere (1), and ionic currents as probes of ocean circulation (2), a major actor in models of climate change. To avoid contamination from local perturbations, measurements of such slowly varying components of the magnetic field must typically be made at a significant height above the Earth's surface (e.g., measurements of components with a spatial-variation scale of 100 km require an altitude of approximately 100 km) and with high sensitivity (on the order of 1 nT). Though magnetic mapping at high altitude has been realized with satellite-born magnetic sensors (3–5), the great expense of multisatellite missions places significant limitations on their deployment and use. Here, we introduce a high-sensitivity ground-based method of measuring magnetic fields from sources near Earth's surface with 100 km spatial resolution.* The method exploits the naturally occurring atomic sodium layer in the mesosphere and the significant technological infrastructure developed for astronomical laser guide stars (LGS). This method promises to enable creation of geomagnetic observatories and of regional or global sensor arrays for continuous mapping and monitoring of geomagnetic fields without interference from ground-based sources.

Overview of Technique

The measurement we envisage is a form of atomic magnetometry, adapted to the conditions of the mesosphere. The principle is to measure spin precession of sodium atoms by spin-polarizing them, allowing them to evolve coherently in the magnetic field, and determining the postevolution spin state. Spin polarization of mesospheric sodium is achieved by optical pumping, as proposed in the seminal paper on sodium LGS by Happer et al. (6). In the simplest realization, the pumping laser beam is circularly polarized and is launched from a telescope at an angle nearly perpendicular to the local magnetic field, as shown in Fig. 1. The magnetic field causes transverse polarization to precess around the field at the Larmor frequency. To avoid "smearing" of atomic polarization by this precession, the optical-pumping rate is modulated near the Larmor frequency, as first demonstrated by Bell and Bloom (7). When the modulation and Larmor frequencies coincide, a resonance results, and a substantial degree of atomic polarization is obtained. The atomic polarization in turn modifies the sodium fluorescence, which is detected by a ground-based telescope, allowing the sodium atoms to serve as a remote sensor of the magnitude of the magnetic field in the mesosphere. Specifically, the resonance manifests itself as a sharp increase in the returned fluorescence for the D_2 line of sodium, or a decrease for the D_1 line, as a function of the modulation frequency. By station-

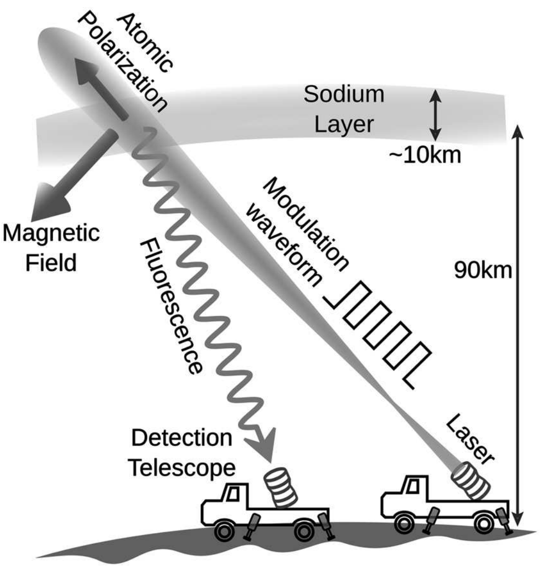

Fig. 1. Fluorescent detection of magneto-optical resonance of mesospheric sodium. (Diagram not to scale.) Circularly polarized laser light at 589 nm, modulated near the Larmor frequency, pumps atoms in the mesosphere. The resulting spin polarization (pictured as instantaneously oriented along the laser beam propagation direction) precesses around the local magnetic field. Fluorescence collected by a detection telescope exhibits a resonant dependence on the modulation frequency.

Author contributions: J.M.H., S.M.R., B.P., R.H., D.B.C., and D.B. performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

*We note that resolution, as used here, refers to the ability to distinguish fields from separate sources. Sources on the Earth's surface produce fields in the mesosphere which vary only over 100-km distances; closer sources, however, such as those in the ionosphere, could be detected in the mesosphere with a spatial resolution substantially better than 100 km.

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ing lasers and detectors on a few 100-km grid, a simultaneous map of magnetic fields may be obtained; alternatively, the laser and detector can be mounted on a relocatable stable platform such as a ship or truck to facilitate magnetic surveying. In contrast to ground-based and satellite-based measurements, the platform is not required to be nonmagnetic or magnetically quiet.

Physical Model

The magnetometric sensitivity of this technique is governed by the number of atoms involved in the measurement, the coherence time of the atomic spins, and detector solid angle. A detailed discussion of mesospheric properties relevant to LGS has recently been given (8). Briefly, the sodium layer has an altitude of approximately 90 km, thickness of approximately 10 km, temperature of 180 K, and number density of $3 \times 10^9\ \mathrm{m}^{-3}$. This density is low by vapor cell standards, but the interaction volume and atom number can be large, limited chiefly by available laser power. The coherence time is set primarily by collisions with other atmospheric molecules and secondarily by atom loss from the region being probed (e.g., due to diffusion or wind). A velocity-changing collision occurring after an atom is pumped typically removes the atom from the subset of velocity classes that are near-resonant with the laser light; as a consequence, these collisions result in an effective decay of spin polarization. Moreover, spin-exchange collisions of sodium atoms with unpolarized paramagnetic species, predominantly O_2, result in a randomization of the electron spin, and therefore also lead to decay of sodium polarization. To our knowledge, the spin-exchange cross-section of oxygen with sodium has not been measured. However, its magnitude can be estimated from other known spin-exchange cross-sections, leading to an expected spin-damping time on the order of 250 μs. Assuming that the detection telescope area is $1\ \mathrm{m}^2$ and the fluorescence is near-isotropic, the fraction of detected photons is approximately 10^{-11}.

The atom number can be maximized either by increasing the interaction volume or by including more velocity classes. Because the most probable atomic velocity component along the laser beam propagation direction is zero, broadening the laser spectrum to include velocity classes away from zero velocity offers diminishing returns as spectral widths approaching the Doppler linewidth (approximately 1 GHz) are reached. By contrast, defocusing the laser beam to illuminate a larger region in space suffers no limitation other than the amount of laser power that can be supplied. The expected relaxation rate, however, can be sharply reduced by broadening the laser linewidth, because velocity-changing collisions become ineffective at depolarization as the laser linewidth approaches the Doppler linewidth. The optimal strategy, then, involves both broadening the laser spectrum to approximately one Doppler linewidth and defocusing the laser beam to the extent permitted by the total laser power. One expects on intuitive grounds that the optimum laser intensity resonant with a single velocity class should be such that the characteristic rate of optical pumping $\Gamma_p \equiv \gamma_0 I/2I_{\mathrm{sat}}$ (where I is the laser intensity, $I_{\mathrm{sat}} \approx 60\ \mathrm{W/m}^2$ is the saturation intensity of the sodium cycling transition, and $\gamma_0 \approx 2\pi \times 10$ MHz is the sodium natural linewidth) is on the same order as the decay rate of atomic polarization.

Because the velocity-changing collision rate is significant on the spin-relaxation timescale but small compared to the natural lifetime of the sodium excited state, the mesospheric conditions represent a unique regime of atomic physics and optical pumping, requiring the development of special theoretical techniques (9) and numerical approaches. To analyze the performance of mesospheric sodium magnetometry, we have performed a detailed numerical ground-state density-matrix analysis of spin precession and optical pumping on the D_1 and D_2 transitions of sodium. In recognition of the importance of redistribution of atoms through velocity-changing collisions, we kept track of a number (in practice, 16) of velocity classes spanning the velocity distribution. We employed a circularly polarized pump laser beam oriented at right angles to a magnetic field of 0.5 G, with a spin-exchange collision time of 250 μs and a velocity-changing collision time of 50 μs. The laser spectrum was taken to be Lorentzian with a half-width at half maximum of 400 MHz, which was found to be near-optimal. Because at this linewidth the sodium excited-state hyperfine structure is unresolved, we have neglected the excited-state hyperfine splittings and assumed the use of a repumping laser to prevent depopulation to the other hyperfine ground state. Because the optical intensity resonant with any velocity group is substantially lower than the saturation intensity, we expect the use of a ground-state calculation to be accurate; we have also performed calculations of the resonance contrast for selected parameters using the full (ground- and excited-state) optical Bloch equations. For a range of values of pump light intensity and duty cycle (the duration of one light pulse divided by the modulation period), we calculate resonance spectra as functions of modulation frequency.

Results and Discussion

Sample spectra for the laser tuned to the D_1 and the D_2 lines are shown in Fig. 2. From the width and peak height of these spectra, we calculate the photon shot-noise-limited magnetometric sensitivity, neglecting technical photometric noise. Our calculation maintains a constant launched pump laser power of 20 W by varying the laser spot size on the mesosphere. Contour plots of sensitivity versus duty cycle and intensity are shown in Fig. 3.

The optimum sensitivity, occurring on the D_1 transition at a duty cycle of 20% and peak pump intensity of $32\ \mathrm{W/m}^2$, is $0.44\ \mathrm{nT}/\sqrt{\mathrm{Hz}}$ (i.e., if magnetic fluctuations within a bandwidth $\Delta\nu$ are measured, the root-mean-square noise floor of the measurement will be $0.44\ \mathrm{nT}\sqrt{\Delta\nu/1\ \mathrm{Hz}}$). This sensitivity is within approximately one order of magnitude of the limit set by quantum spin-projection noise, the difference being due to hyperfine structure and Doppler broadening. The optimum on the D_1 line offers superior magnetometric sensitivity in part because the D_1

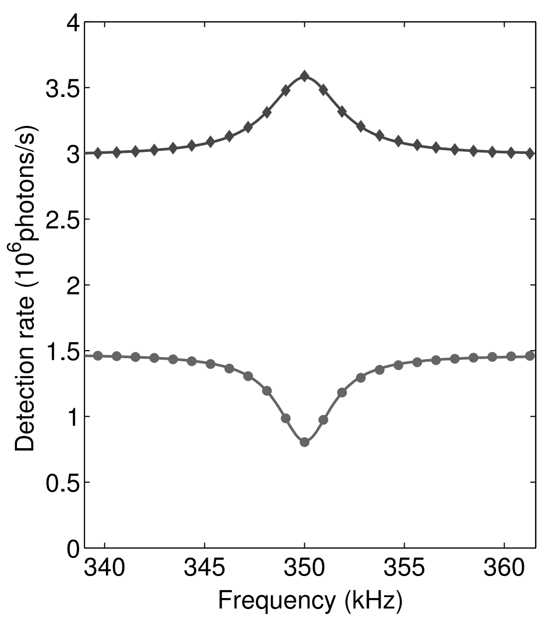

Fig. 2. Calculated magneto-optical resonance profiles for mesospheric sodium. The resonances shown correspond to the D_2 (upper curve, blue diamonds) and D_1 (lower curve, green circles) sodium lines. Symbols are the results of numerical calculations, and solid lines are Lorentzian fits to these results. Calculations are for an intensity $I = 28\ \mathrm{W/m}^2$, a laser linewidth of 400 MHz, and a modulation duty cycle of 20% with a detector collection area of $1\ \mathrm{m}^2$.

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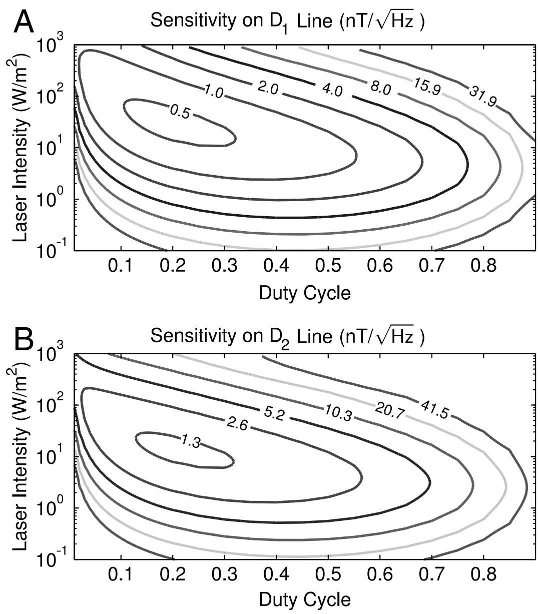

Fig. 3. Contour plot of calculated magnetometer sensitivity as a function of pumping duty cycle and intensity. Sensitivity is calculated using a laser linewidth of 400 MHz, a detector area of 1 m^2, a spin-exchange collision time of 250 μs, and a velocity-changing collision time of 50 μs. Contours are logarithmically spaced at intervals of one octave.

resonances are dark, i.e., they have reduced fluorescence, with correspondingly reduced photon shot noise and broadening. If technical rather than fundamental noise sources dominate, then the D_2 resonance may be preferable for its larger signal size. The D_2 line is routinely used by existing LGS lasers, whereas the D_1 line should be readily attained by these same lasers with minimal modifications.

The calculated magnetometric sensitivity, which is limited by currently available laser power and may therefore be expected to improve with advances in laser technology, is useful for the envisaged geophysical applications, which require measurement of fields, e.g., in the 1–10 nT range for ocean circulation (2) and the tens of nanotesla range for the solar quiet dynamo (1); moreover, the dynamic range of the measurement is not subject to any apparent physical limit, as the resonance technique works well and with similar sensitivity at any magnetic-field strength. The sensitivity of this technique could be further enhanced by as much as five orders of magnitude by detecting the transmitted laser beam instead of being limited to the small fraction of fluorescence emitted toward the detecting telescope. Such enhanced light collection could be achieved with a rocket- or satellite-born retroreflector, or even by employing a satellite-mounted photodetector or pump laser. Though lacking the appealing simplicity of an entirely ground-based apparatus, such a hybrid approach has the potential of extremely high sensitivity, without the challenging magnetic cleanliness requirements of spacecraft-born sensors.

We note also that at the cost of increasing the relaxation rate, the excited-state hyperfine structure can be spectrally resolved by using a narrow-linewidth laser, potentially allowing detection of magneto-optical resonances involving higher polarization multipoles such as alignment (prepared by pumping with linearly polarized light) (10). This capability has the additional practical implication that magnetic fields in the mesosphere could be efficiently sensed in regions (e.g., near the poles) where the Earth's magnetic field is near-vertical. In such locations it is more practical for the pump laser beam to be parallel to the field than perpendicular, a geometry suitable for magnetometers based on atomic alignment but not for those employing atomic orientation.

Although the laser beam intensity in the mesosphere is not high by laboratory standards, the possibility of accidental illumination of aircraft and satellites must be taken into account. The safety of magnetometric measurements, however, is not substantially different from present-day LGS observations, and will be assured by existing protocols for shutting off the pump laser to accommodate occasional flyovers, either prescheduled or monitored in real time.

Because the width of the resonance at the optimum sensitivity is around 5 kHz, effects that are important in other atomic magnetometers such as the quadratic Zeeman shift, which splits the resonance by approximately 150 Hz, and the natural magnetic inhomogeneity (11), which broadens the resonance by approximately 700 Hz, are relatively minor. Temporal variations of the magnetic field are, in principle, merely part of the measured signal, and not an instrumental limitation. However, large enough fluctuations could make it difficult to track the resonance frequency. We take as a likely upper bound for the magnetic fluctuations on timescales of 1–100 s a typical observed value at the Earth's surface of around 1 nT. As this value is again substantially smaller than the resonance linewidth, we expect that except during magnetic storms, it should not be difficult to keep the laser modulation frequency on resonance. Variations of the height and density of the sodium layer itself are an additional practical concern. A real measurement will require reducing sensitivity to such variations through comparison of on-resonant and off-resonant signals, e.g., by dithering the modulation frequency or by employing spatially separated pump beams with different modulation frequencies. Our calculation further assumes that optical shot noise from the detected fluorescence is the dominant noise source; if daytime operation is desired, we calculate that the spectral intensity of scattered background light will be comparable to or somewhat larger than the fluorescence signal. This background can be mitigated by detecting the fluorescence synchronously with the pump-laser modulation, though at the cost of increased technical complexity.

A further deviation from the idealized calculation comes from turbulence in the lower atmosphere, which results in different, random phase shifts of the laser beam in different patches of space. In typical LGS applications, the far-field diffraction pattern in the mesosphere from these phase patches consists of filaments whose individual lateral size is set by the numerical aperture of the laser launch telescope, but whose collective extent is governed (12) by the patch size (approximately 0.1 m). Fluctuation of these filaments in time results in undesirable changes in pump-laser intensity, motion of the illuminated column, and variation of the returned fluorescence. Although these effects will prevent fine-tuning of laser intensity, we do not anticipate that such variations will strongly affect the sensitivity obtainable with the proposed technique. We plan to perform detailed modeling of atmospheric effects using physical optics, as has recently been done with reference to LGS (8, 13).

Conclusion

In summary, we have presented a promising method that complements and may in some cases replace satellite missions for the measurement of geomagnetic fields. The proposed method requires only ground-based apparatus and is consequently substantially less expensive per sensor than a satellite formation, but still achieves high magnetometric sensitivity. We anticipate that the low cost of deployment will make possible large-scale magnetic mapping and monitoring applications at the 100-km length scale, with temporal and spatial coverage that would be difficult to obtain by other techniques. Furthermore, as satellites cannot be operated as low as 100 km in altitude without excessive drag and heating, remotely detected mesospheric magnetometry promises superior spatial resolution of terrestrial sources. In addition, the technique promises to make it possible to install geomagnetic observatories in areas that are not sufficiently remote or magnetically clean for ground-based measurements, supplementing existing magnetic observatory data. An intriguing possibility is the use of a mobile or relocatable platform (which need not be made of nonmagnetic materials) for high-precision magnetic monitoring. We are currently constructing a 20-W-class laser projection system and working to implement this technique in proof-of-principle magnetic-field measurements.

ACKNOWLEDGMENTS. The authors acknowledge stimulating discussions with Peter Milonni, William Happer, Michael Purucker, and Stuart Bale. This work is supported by the National Geospatial-Intelligence Agency University Research Initiatives program.

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