CUME Exam #346
Saturday, September 26th, 2009
Developed and Administered by: Jim Murphy

This exam is focused upon topics related to the accompanying paper, "Mars Water-Ice Clouds and Precipitation" by Whiteway et al (SCIENCE, 325, July 03, 2009).

The *a priori* anticipated PASS grade is a 70% (40.25 out of 57.5 available points).

Start your answers to each **SECTION** on a new sheet of paper, write only on a single side of the sheets of paper on which you write your answers, and when complete staple your answer pages together in SECTION and numerical question order.

Some possibly useful information:

Mars' radius	3395 km
Mars' surface gravitational acceleration	3.7 m s^{-2}
Mars' orbital semi-major axis	1.52 AU (1 AU = 1.5 x 10^8 km)
Mars' orbital eccentricity	0.093
Mars' Geometric Albdeo	0.15
Mars' Bond Albedo	0.16
Mars' equilibrium temperature	216 Kelvin
Mars' globally averaged surface pressure	610 Pascals
CO_2 specific heat at constant pressure	735 J kg^{-1} K^{-1}
Gas Constant for CO_2	189 J kg^{-1} K^{-1}
Atmospheric surface pressure at the PHOENIX site	840 Pascals
Latent heat of H_2O vaporization	2.5 x 10^6 J kg^{-1}
Latent heat of H_2O fusion (freezing)	3.3 x 10^5 J kg^{-1}
Solar flux intensity received by Earth	1370 W m^{-2}
Divergence of the emitted 532 nm LIDAR beam	0.25 mrad

SECTION I: THE PHOENIX MISSION ITSELF (20 points)

For Questions 1 and 2, assume that the PHOENIX Lander was launched toward Mars along a **minimum-energy** (so-called "Hohmann") **transfer orbit path**. Assume that the planets' orbits have zero eccentricity when answering these two questions. These first three questions do not require you to have read the accompanying paper by Whiteway et al.

---

1) Draw a figure that illustrates the orbit paths of Earth, Mars, and the PHOENIX Lander, and **calculate** the length of time (in Earth-months) required for the PHOENIX Lander to travel from Earth to Mars along this minimum energy orbit path. **[5 points]**

---

2) Quantitatively compare the orbit speeds of Mars and the PHOENIX Lander at a distance of 1.52 AU from the Sun. Assume that Mars' orbital eccentricity is zero for this comparison. **Then, discuss** what this quantitative comparison of the two orbit velocities suggests about the geometry of PHOENIX's entry in to Mars' atmosphere. For instance, what would be a reasonable estimate of the range of local times available at Mars' surface radially below PHOENIX's atmospheric entry point? **[7.5 points]**

3) Assume that the PHOENIX Lander entered radially downward in to Mars' atmosphere upon its arrival at Mars, and that the atmosphere's vertical temperature structure was isothermal. **Construct an equation** which if numerically integrated would provide a quantified estimate of the speed the heat-shield protected spacecraft would have had at Mars' surface (where the pressure was 840 Pascals) if no parachute had been deployed and no retrorockets had fired. Provide an explanation of the terms you include in your equation. **[7.5 points]**

SECTION II: THE PHOENIX LIDAR INSTRUMENT (15.0 points)

The PHOENIX LIDAR instrument operated at a wavelength of 532 nm for the analyses conducted and described in the accompanying Whiteway et al. paper.

4) Construct an equation that describes the intensity of emitted LIDAR flux that the LIDAR would receive (measure) back as scattered flux from the bottom 50 meters (2.95-3.00 km altitude range) of the upper cloud indicated in Figure 1B. Describe the terms you include in your equation. Assume that there are no instrumental problems to worry about. **[7.5 points]**

---

5) Describe how the physical characteristics of the martian atmosphere AND the physical characteristics of the dust suspended within the atmosphere would result in a LIDAR instrument operating at a wavelength of 15 micrometers being a **BAD CHOICE** for conducting the scientific investigation described in the accompanying Whiteway et al. paper. **[7.5 points]**

SECTION III: THE MARS ENVIRONMENT EXPERIENCED BY THE PHOENIX LANDER (22.5 points)

6) On page 69 of the paper, the authors indicate that they estimate the column water ice cloud mass to amount to 1.9 g m^{-2}. **Quantitatively demonstrate** that it is appropriate that the paper <u>does not focus</u> on the thermodynamic (temperature) effects of this condensing (actually, deposition, since temperatures are below freezing) and subliming water upon the thermal state of the martian atmosphere. Such water condensation/evaporation processes are important within Earth's atmosphere. **[7.5 points]**

---

7) Describe how the atmospheric thermodynamic conditions (atmospheric temperature and frost temperature) indicated in Figure 1C for the 5 AM time period are physically consistent with the vertical profile of extinction indicated in Figure 1B. **[7.5 points]**

---

8) Under current conditions, liquid water is not stable on Mars' surface.

a) Discuss if it is physically (but probably not realistically) possible to change Mars' solid surface characteristics to enable Mars' equilibrium temperature to increase to the point where liquid water could be thermally stable on Mars' surface. **[5.0 points]**

b) Then, discuss a major atmospheric physical characteristic that would make it difficult for Mars' surface environment to sustain liquid water on the surface even if surface temperatures were sufficiently warmed due to changed solid surface characteristics. **[2.5 points]**

Mars Water-Ice Clouds and Precipitation

J. A. Whiteway,[1*] L. Komguem,[1] C. Dickinson,[1] C. Cook,[1] M. Illnicki,[1] J. Seabrook,[1] V. Popovici,[1] T. J. Duck,[2] R. Davy,[1] P. A. Taylor,[1] J. Pathak,[1] D. Fisher,[3] A. I. Carswell,[4] M. Daly,[5] V. Hipkin,[6] A. P. Zent,[7] M. H. Hecht,[8] S. E. Wood,[9] L. K. Tamppari,[8] N. Renno,[10] J. E. Moores,[11] M. T. Lemmon,[12] F. Daerden,[13] P. H. Smith[11]

The light detection and ranging instrument on the Phoenix mission observed water-ice clouds in the atmosphere of Mars that were similar to cirrus clouds on Earth. Fall streaks in the cloud structure traced the precipitation of ice crystals toward the ground. Measurements of atmospheric dust indicated that the planetary boundary layer (PBL) on Mars was well mixed, up to heights of around 4 kilometers, by the summer daytime turbulence and convection. The water-ice clouds were detected at the top of the PBL and near the ground each night in late summer after the air temperature started decreasing. The interpretation is that water vapor mixed upward by daytime turbulence and convection forms ice crystal clouds at night that precipitate back toward the surface.

The seasonal hydrological cycle on Mars is most evident in the Arctic region, where the atmospheric water vapor abundance increases to a maximum in midsummer after the seasonal ground ice cover reaches a minimum (*1*). The water returns to the surface as the atmosphere cools in late summer, but it has not previously been known whether this process involves clouds and precipitation as on Earth. Observations of water vapor and temperature during the Viking missions indicated that the atmosphere would be saturated with respect to water ice at night (*2*, *3*), and it was suggested that the precipitation of ice crystals could be an important factor for the exchange of water between the atmosphere and surface (*4*). Here we report on experimental evidence that clouds and precipitation play a role in the exchange of water between the atmosphere and ground on Mars.

The Phoenix mission (*5*, *6*) obtained measurements from the surface in the Arctic region of Mars (68.22°N, 234.25°E). The spacecraft landed before the summer solstice on Mars and operated over the next 5 months. This period encompasses the midsummer peak and decline in the abundance of atmospheric water vapor, so it was possible to observe the local processes that contribute to the water cycle. The Phoenix mission included a light detection and ranging (LIDAR) instrument (*7*) that emitted pulses of laser light upward into the atmosphere and detected the backscatter from dust and clouds. An essential capability of the LIDAR was that it could resolve the internal structure of water-ice clouds that drifted past the landing site.

Daytime LIDAR observations mainly detected dust in the atmosphere. The measurements on the 45th sol (*8*) after landing were typical for moderate dust loading with no clouds (Fig. 1A). The dust was distributed evenly up to a height of 4 km because of the daytime vertical mixing produced by convection and turbulence within the planetary boundary layer (PBL). The atmospheric dust loading reached a peak around the summer solstice and then generally decreased. On sol 97 [solar longitude of Mars (L_s) = 121°], the dust loading within the PBL was reduced by a factor of 3 in comparison with that on sol 45 (Fig. 1A).

During the period around the summer solstice, clouds were observed sporadically and mainly above heights of 10 km. Moving into late summer, 50 sols after the solstice (L_s = 113°), the LIDAR detected a regular pattern of cloud formation each night within the PBL. A shallow surface-based cloud formed near midnight (Mars local solar time), and a second cloud layer formed after 1 a.m. at heights around 4 km. On sol 99 (L_s = 122°), there was a clear enhancement in the extinction coefficient due to the presence of clouds in the height range from 3 to 4 km and in the layer up to 1 km above the ground (Fig. 1B). The observed clouds formed at an estimated temperature of around −65°C (Fig. 1C), which is consistent with clouds that are composed of water-ice crystals (the frost point for carbon dioxide is less than −120°C). On each sol during the second half of the mission (L_s = 113° to 150°), clouds remained through the early morning hours and then dissipated when the atmosphere warmed sufficiently during the daytime. As the summer progressed toward autumn and the air temperature decreased, the clouds persisted longer into the morning hours and ex-

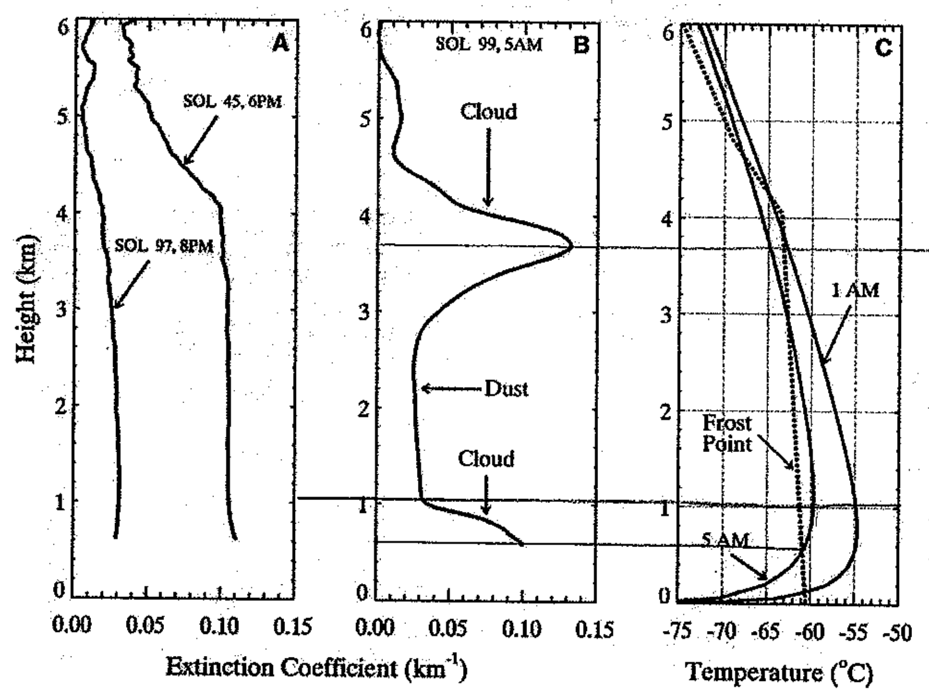


Fig. 1. (**A** and **B**) Profiles of the optical extinction coefficient (*9*) derived from the LIDAR backscatter signal at wavelength 532 nm for sols 45 (L_s = 97°), 97 (L_s = 121°), and 99 (L_s = 122°). Each profile is averaged over 1 hour and smoothed for a vertical resolution of 40 m. (**C**) Height profiles of atmospheric temperature estimated with a numerical simulation model of the martian PBL (*19*, *20*), and an estimate of the profile of frost point temperature.

[1]Department of Earth and Space Science and Engineering, York University, Toronto, Ontario, Canada. [2]Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia. [3]National Glaciology Group, Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario, Canada. [4]Optech, Vaughan, Ontario, Canada. [5]MacDonald, Dettwiler and Associates (MDA), Brampton, Ontario, Canada. [6]Canadian Space Agency (CSA), St-Hubert, Quebec, Canada. [7]NASA Ames Research Center, Moffett Field, CA, USA. [8]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. [9]Department of Earth and Space Sciences, University of Washington, Seattle, WA, USA. [10]Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI, USA. [11]Department of Planetary Sciences, University of Arizona, Tucson, AZ, USA. [12]Department of Atmospheric Sciences, Texas A&M University, College Station, TX, USA. [13]Belgian Institute for Space Aeronomy (BIRA-IASB), Brussels, Belgium.

*To whom correspondence should be addressed. E-mail: whiteway@yorku.ca

tended further toward the ground. Clouds were not detected in the late afternoon or evening.

The outline and internal structure of the clouds that drifted above the Phoenix landing site are seen in the contour of the backscatter coefficient (*9*). On sol 99 (Fig. 2A), the most striking features are the tilted vertical streaks after 05:00 (Mars local time). This pattern is consistent with ice crystals precipitating from the cloud and eventually sublimating in the subsaturated air below the cloud. Such fall streaks are a well-known feature in observations of cirrus clouds on Earth.

In the early morning hours on sol 109, the LIDAR observed clouds and precipitation that extended all the way to the ground (Fig. 2B). In the period between 03:10 and 03:50, there were water-ice clouds at the top of the PBL (at heights of 3 to 5 km) and at ground level. In the next LIDAR run, from 05:16 to 05:45, the base of the observed cloud had dropped to a height of about 1.5 km, and there were precipitation fall streaks starting at 05:30 that extended down through the ground-level cloud. The LIDAR is not able to measure below about 50 m because of the geometry of the transmitter/receiver overlap. It is reasonable to assume that the ice crystals would have continued to descend through the saturated air to reach the surface. The essential point here is that precipitation moves water toward the surface from heights of up to 5 km (*10*).

In the period around sol 99 (L_s = 122°), clouds were observed only after 01:00, so we take this as the time when clouds were initially forming. The average fall speed required to produce a fall streak length of 1.2 km (Fig. 2A) after 4 hours is consistent with an ellipsoidal ice particle with an aspect ratio of 3 and volume equivalent to a sphere with a radius of 35 μm (*11*). This approximates a columnar ice crystal 42 μm wide and 127 μm long, which is similar to ice crystals that have been sampled in cirrus clouds on Earth (*12*, *13*). The comparison is not surprising, because cirrus clouds on Earth form at a similar temperature and water vapor density.

The extinction coefficient represents the effective cross-sectional area of the ice crystals per unit of volume and, assuming spherical particles, the ice water content can be calculated as IWC = $4\sigma R_{eff}\rho/3Q$. σ is the extinction coefficient; R_{eff} is the effective radius, which we assumed to be 35 μm based on the calculation of fall speed; Q is the scattering efficiency, which has a value of 2; and ρ is the density of water ice. The enhancement in the extinction coefficient due to the cloud in the average signal profile (Fig. 1B) has a peak value of 0.1 km^{-1}, but the range is from 0.07 to 0.27 km^{-1} in profiles with shorter averages. The corresponding estimates of IWC for spherical particles are in the range of 1.5 to 5.8 mg m^{-3}, and this is also similar to measurements of cirrus clouds on Earth (*14*). The spherical assumption can be avoided by using the empirical relationship between the extinction coefficient and IWC that was derived from aircraft in situ measurements in cirrus clouds (*14*): IWC = 119 $\sigma^{1.22}$. This gives a similar range of values: 1.0 to 5.3 mg m^{-3}. Using the empirical relationship, the amount of ice water integrated in the vertical (from the mean profile of Fig. 1B) is 1.9 g m^{-2}, which has the same value in units of precipitable micrometers (pr-μm) of water. This is more than substantial enough to play a role in the seasonal decreasing trend of about 0.5 pr-μm per sol in the local column water vapor (from L_s = 120° to 160°) measured from orbit (*1*).

We estimated the amount of water vapor within the PBL from the height and time of cloud formation, combined with the simulated temperature. For cloud formation commencing at 01:00 at a height of 4 km, the simulated temperature is –64.3°C (Fig. 1C), and the corresponding saturated vapor pressure is 0.61 Pa. The threshold relative humidity over ice for nucleation on desert dust has been measured in the laboratory to be in the range from 110 to 130% (*15*). Thus, we assumed that the water vapor pressure at a height of 4 km when the cloud started to form was 20% greater than the saturated value: 0.61 × 1.2 = 0.73 Pa. At the height of 4 km, the water vapor volume mixing ratio before cloud formation is 0.73/522 = 0.0014, where the model atmospheric pressure is 522 Pa. The uncertainty in this estimate is about ±20%, based on the range in the possible cloud formation times and the ice nucleation threshold. It is also assumed here that water vapor was well mixed throughout the PBL by the daytime

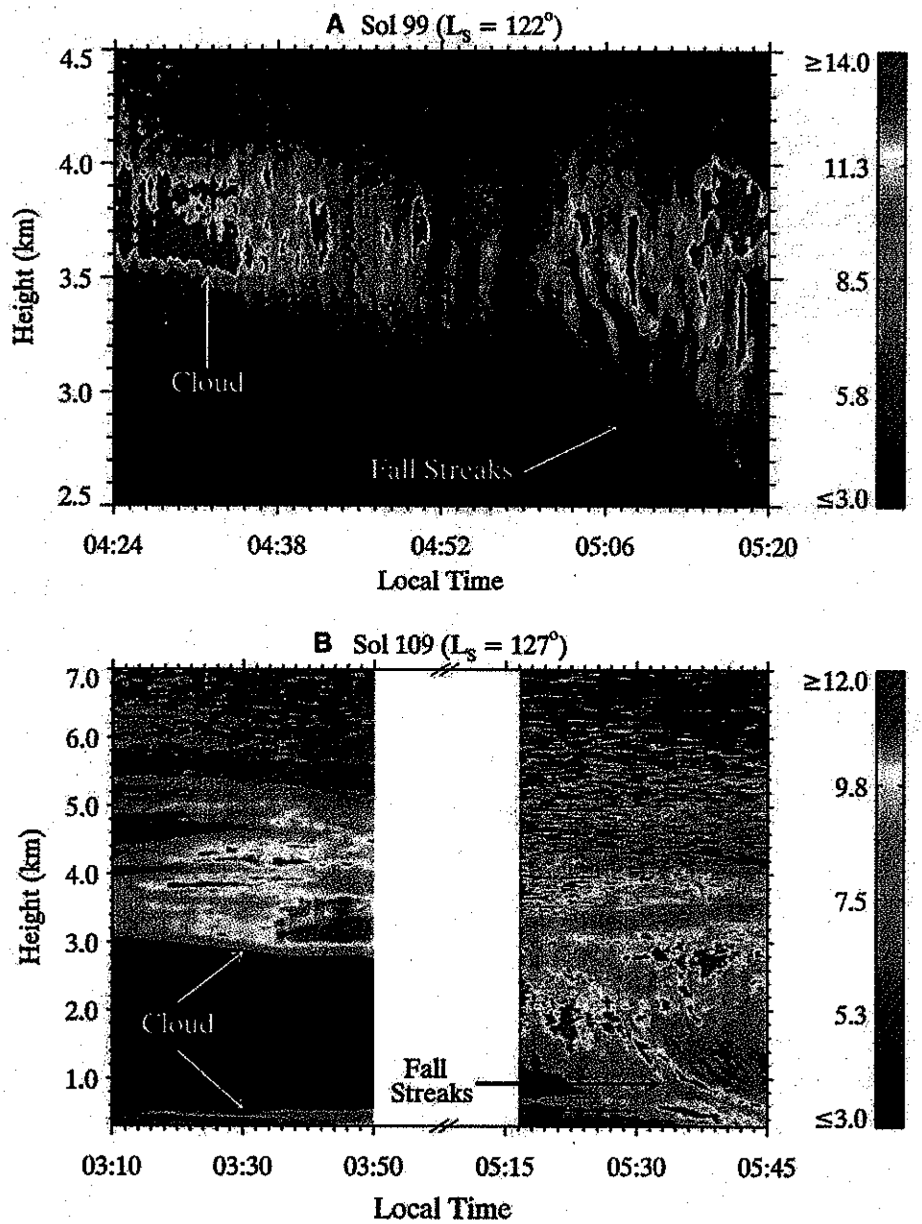


Fig. 2. Contour plots of backscatter coefficient (×10^{-6} m^{-1} sr^{-1}) derived from the LIDAR backscatter signal (*9*) at wavelength 532 nm on mission sols 99 (L_s = 122°) (**A**) and 109 (L_s = 127°) (**B**).

turbulence and convection, so that in the early evening, the mixing ratio of water vapor was approximately constant up to a height of 4 km. Above the cloud top, the water vapor partial pressure would have been below the saturation value because clouds were not observed at those heights. The corresponding height profile of frost point temperature (before cloud formation) is shown in Fig. 1C. The integrated amount of water vapor within the PBL (from the ground to 4 km) before cloud formation on sol 99 (L_s = 122°) can be estimated from the analysis above to be 35 pr-μm. This is a substantial fraction of the total atmospheric column water vapor (40 to 50 pr-μm) measured from orbit at the latitude of Phoenix in previous years (*1*, *16*). Solar radiation measurements during the Pathfinder mission also indicated that atmospheric water vapor was confined near the ground (*17*).

We also used the simulated temperature profiles in Fig. 1C to estimate the IWC in the clouds. At 05:00 and a height of 4 km, the simulated temperature is −66°C and the saturated vapor density is 5 mg m^{-3}. The threshold value of vapor density at cloud formation (time 01:00) was 7.6 mg m^{-3}. The difference of 2.6 mg m^{-3} is an estimate of the IWC in the cloud, and this is within the range of IWC derived from the LIDAR measurements.

Our estimate of the water content of the PBL is consistent with independent measurements. The Thermal and Electrical Conductivity Probe instrument (*18*) on Phoenix measured the partial pressure of water vapor near the ground to have values up to 2 Pa during the daytime and less than 0.1 Pa at night, with a diurnal average of 0.9 Pa (*6*). The water vapor volume mixing ratio in the mixed boundary layer would be greater than the average at ground level (0.0012), because the vertical mixing occurs mainly during the daytime. Also, if the water vapor volume mixing ratio was 0.0016 throughout the PBL, then the integrated amount up to a height of 4 km would be 40 pr-μm, and this is an upper limit because it is within the measured range of the total atmospheric column water vapor (*1*, *16*). Our estimate of the volume mixing ratio at the top of the PBL (0.0014) is within the range of plausible values.

The Phoenix LIDAR observations have demonstrated that water-ice crystals grow large enough to precipitate through the atmosphere of Mars. In the early morning hours, the clouds formed at ground level and at heights around 4 km because these were the coldest parts of the PBL (Fig. 1C). The cloud was capped at the top of the PBL because daytime turbulent mixing does not transport moisture above that height. The overall process was that water ice was transported downward by precipitation at night, it sublimated in the morning, and then the vapor was mixed back up through the PBL by turbulence and convection during the daytime. The clouds and precipitation act to confine water within the PBL. Eventually the ice clouds would have persisted within the PBL throughout the daytime, and water ice would have remained deposited on the ground. As the depth of the PBL decreased in late summer, this local process would contribute to the seasonal decrease in atmospheric water vapor (*1*).

References and Notes

1. M. D. Smith *et al.*, *J. Geophys. Res.* **107**, 5115 10.1029/2001JE001522 (2002).
2. D. Davies, *J. Geophys. Res.* **84**, 8335 (1979).
3. J. Ryan *et al.*, *J. Geophys. Res.* **87**, 7279 (1982).
4. R. A. Kahn, *J. Geophys. Res.* **95**, 14677 (1990).
5. P. H. Smith *et al.*, *J. Geophys. Res.* **113**, E00A18 (2008).
6. P. H. Smith *et al.*, *Science* **325**, 58 (2009).
7. J. A. Whiteway *et al.*, *J. Geophys. Res.* **113**, E00A08 10.1029/2007JE003002 (2008).
8. A sol is a martian day, with a length of 24.6 hours. Phoenix landed 30 sols before the Mars summer solstice, when solar longitude is L_s = 90°.
9. Materials and methods are available as supporting material on *Science* Online.
10. Further evidence of precipitation was observed in images of low-level clouds (supporting online material text).
11. N. A. Fuchs, *The Mechanics of Aerosols* (Pergamon, New York, 1964).
12. J. A. Whiteway *et al.*, *Geophys. Res. Lett.* **31**, L24102 (2004).
13. M. W. Gallagher *et al.*, *Q. J. R. Meteorol. Soc.* **131**, 1143 (2005).
14. A. J. Heymsfield *et al.*, *Geophys. Res. Lett.* **32**, L10807 (2005).
15. P. R. Field *et al.*, *Atmos. Chem. Phys.* **6**, 2991 (2006).
16. H. Tschimmel *et al.*, *Icarus* **195**, 557 (2008).
17. D. V. Titov *et al.*, *J. Geophys. Res.* **104**, 9019 (1999).
18. A. P. Zent *et al.*, *J. Geophys. Res.* **114**, E00A27 (2009).
19. R. Davy *et al.*, *J. Geophys. Res.* **114**, D04108 (2009).
20. For the simulations used here, the upper-level wind was assumed to be as 5 m s^{-1}. The temperature and pressure at ground level were matched to the Phoenix in situ measurements, and the height distribution of dust was based on the Phoenix LIDAR observations. The model predicts a PBL depth of 4 km, which is consistent with the LIDAR daytime dust observations (Fig. 1A).

21. We acknowledge contributions to landed operations from the engineering staff at the CSA (P. Allard, C. Brunet, D. Cormier, I. Tremblay, and E. Vachon) and MDA Space Missions (D. Hill, L. Clark, A. Kerr, and R. McCoubrey). This work was enabled by funding from the CSA under contract 9F007-070437/001/SR. The Phoenix mission was led by the University of Arizona, on behalf of NASA, and managed by the Jet Propulsion Laboratory.

Supporting Online Material
www.sciencemag.org/cgi/content/full/325/5936/68/DC1
Materials and Methods
SOM Text
Fig. S1
Movie S1
References

16 February 2009; accepted 27 May 2009
10.1126/science.1172344

A Coherent Single-Hole Spin in a Semiconductor

Daniel Brunner,[1] Brian D. Gerardot,[1] Paul A. Dalgarno,[1] Gunter Wüst,[1] Khaled Karrai,[2] Nick G. Stoltz,[3] Pierre M. Petroff,[3] Richard J. Warburton[1,4]*

Semiconductors have uniquely attractive properties for electronics and photonics. However, it has been difficult to find a highly coherent quantum state in a semiconductor for applications in quantum sensing and quantum information processing. We report coherent population trapping, an optical quantum interference effect, on a single hole. The results demonstrate that a hole spin in a quantum dot is highly coherent.

Semiconductor heterostructures can be designed to confine electrons, holes, and photons in specific ways. Post-growth processing enables the creation of individual devices and their interconnection into fully functional circuits. However, it is not yet clear whether these material advantages can be exploited in a new class of device whose operation depends on the controlled manipulation of coherent quantum states. Achieving the necessary coherence poses considerable challenges.

In bulk semiconductors and quantum wells, individual quantum states lose coherence rapidly through an interaction with the lattice vibrations, or phonons. An electron spin interacts only indirectly via the spin-orbit interaction with the phonons and emerges as a strong candidate quantum bit (qubit) (*1*). However, to suppress the spin-orbit interaction, the electron must be tightly confined to a nanoscopic quantum dot (*2*–*4*). But in GaAs, the semiconductor with the best materials properties, the electron spin now interacts with 10^4 to 10^5 nuclear spins, too few for cancellation of the hyperfine interaction and too many for each nuclear spin to be used as a resource. The nuclear spins create a fluctuating effective magnetic field, the Overhauser field. The electron spin processes in the Overhauser field such that the time-averaged coherence time, T_2*, is small, just ~10 ns (*5*–*7*), much less than the intrinsic decoherence time, T_2, which is around 1 μs (*8*, *9*). This difficulty represents a stumbling block in engineering a coherent semiconductor spin state.

[1]School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK. [2]Department für Physik der Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, 80539 Munich, Germany. [3]Materials Department, University of California, Santa Barbara, CA 93106, USA. [4]Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland.

*To whom correspondence should be addressed. E-mail: r.j.warburton@hw.ac.uk

CUME Exam #346
Saturday, September 26th, 2009

Developed and Administered by: Jim Murphy

This exam is focused upon topics related to the accompanying paper, "Mars Water-Ice Clouds and Precipitation" by Whiteway et al (SCIENCE, 325, July 03, 2009).

The *a priori* anticipated PASS grade is a 70% (42.0 out of 60.0 available points).

Start your answers to each **SECTION** on a new sheet of paper, write only on a single side of the sheets of paper on which you write your answers, and when complete staple your answer pages together in SECTION and numerical question order.

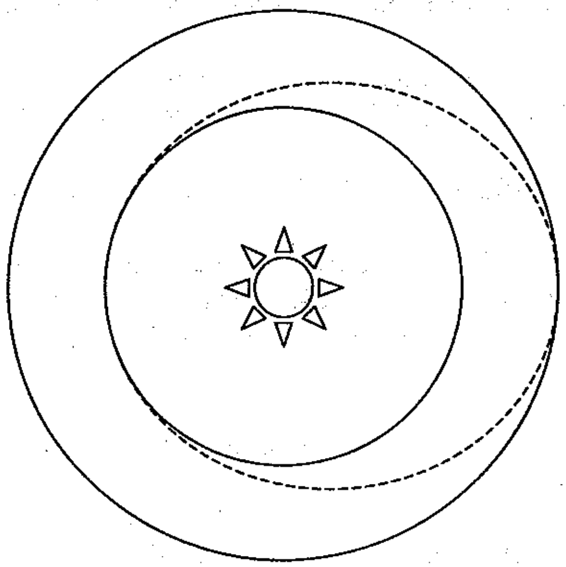
Some possibly useful information:

Mars' radius	3395 km
Mars' surface gravitational acceleration	3.7 m s^{-2}
Mars' orbital semi-major axis	1.52 AU (1 AU = 1.5 x 10^8 km)
Mars' orbital eccentricity	0.093
Mars' Geometric Albdeo	0.15
Mars' Bond Albedo	0.16
Mars' globally averaged surface pressure	610 Pascals
CO_2 specific heat at constant pressure	735 J kg^{-1} K^{-1}
Gas Constant for CO_2	189 J kg^{-1} K^{-1}
Atmospheric surface pressure at the PHOENIX site	840 Pascals
Latent heat of H_2O vaporization	2.5 x 10^6 J kg^{-1}
Latent heat of H_2O fusion (freezing)	3.3 x 10^5 J kg^{-1}
Solar flux intensity received by Earth	1370 W m^{-2}
Divergence of the emitted 532 nm LIDAR beam	0.25 mrad

SECTION I: THE PHOENIX MISSION ITSELF (20 points)

For Questions 1 and 2, assume that the PHOENIX Lander was launched toward Mars along a **minimum-energy** (so-called "Hohmann") **transfer orbit path**. Assume that the planets' orbits have zero eccentricity when answering these two questions. These first three questions do not require you to have read the accompanying paper by Whiteway et al.

1) Draw a figure that illustrates the orbit paths of Earth, Mars, and the PHOENIX Lander, and **calculate** the length of time (in Earth-months) required for the PHOENIX Lander to travel from Earth to Mars along this minimum energy orbit path. [**5 points**]



OSA of transfer orbit is 1.26 AU [= (1.52 AU + 1.0 AU) / 2]

Kepler's 3rd Law: $P^2 = OSA^3$ $P = 1.26^{3/2} = 1.414$ Earth Years

Travel time is one-half of the orbit duration, so travel time is 0.707 Earth years (~8.5 months)

2) Quantitatively compare the orbit speeds of Mars and the PHOENIX Lander at a distance of 1.52 AU from the Sun. (Assume that Mars' orbital eccentricity is zero for this comparison).

Then, discuss what this quantitative comparison of the two orbit velocities suggests about the geometry of PHOENIX's entry in to Mars' atmosphere. For instance, what would be a reasonable estimate of the range of local times available at Mars' surface radially below PHOENIX's atmospheric entry point? [**7.5 points**]

Mars orbit speed = $(GM/a_{Mars})^{1/2}$
$= ((6.67 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2} \times 2 \times 10^{30}\ kg) / (1.52 \times 1.5 \times 10^{11}\ m))^{1/2}$
$= 24{,}189\ m\ s^{-1}$

PHOENIX orbit speed at 1.52 AU = $(GM\ (2/r - 1/aPHX))^{1/2}$
$= ((6.67 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2} \times 2 \times 10^{30}\ kg) \times (((2/1.52) - (1/1.26))*1.5 \times 10^{11}\ m))))^{1.2}$
$= 21,\ 549\ m\ s^{-1}$

So, Mars' orbit speed is ~2600 m s^{-1} faster than PHOENIX's at 1.52 AU.
Since Mars is traveling faster, and the two bodies should be traveling parallel to each other when they meet (for this situation described), we can consider that Mars will 'catch up to' PHOENIX, which would imply that PHOENIX will enter in to Mars' atmosphere on Mars' leading 'side' which would encompass the local times from midnite to noon local time.

3) Assume that the PHOENIX Lander entered radially downward in to Mars' atmosphere upon its arrival at Mars, and that the atmosphere's vertical temperature structure was isothermal. **Construct an equation** which if numerically integrated would provide a quantified estimate of the speed the heat-shield protected spacecraft would have had at Mars' surface (where the pressure was 840 Pascals) if no parachute had been deployed and no retrorockets had fired. Provide an explanation of the terms you include in your equation. **[7.5 points]**

$$V_{sfc} = V_{Z=top} - \int [(1/2)\, \rho(Z)\, V(Z)^2]\, [\, Drag\, \pi\, r_{PHX}^2 / Mass_{PHX}] + GM_{Mars}/(r_{Mars} + Z)^2\, dz$$

$$= V_{Z=top} - \int [(1/2)\, \rho_{sfc}\, e^{-Z/H}\, V(Z)^2]\, [Drag\, \pi\, r_{PHX}^2] / Mass_{PHX}] - GM_{Mars} / (r_{Mars} + Z)^2\, dz$$

Where: $V_{Z=top}$ is PHOENIX's radial velocity relative to Mars' surface as it enters the 'top' of the atmosphere (maybe 125 km altitude..)

- the dynamic pressure imposed upon the spacecraft will be due to the gas density being experienced (which is easily calculated as an exponential since the atmosphere is assumed to be isothermal) and the velocity of the lander; H = Atmospheric Scale Height (= R_{CO2} T / g)
- the dynamic pressure will be imposed upon the cross-sectional area of the spacecraft (its heat shield), with a drag coefficient also important to consider (this will change as a function of Reynolds number, mean free path conditions, angle of attack, etc.)
- the mass of the entry system ($Mass_{PHX}$), since to convert the dynamic pressure into an acceleration requires accounting for the mass of the craft
- the continued downward acceleration of gravity must be retained even while the atmosphere dynamic drag is slowing the spacecraft's descent speed
- Z would be a function of time, so the numerical integral would be formulated over time

SECTION II: THE PHOENIX LIDAR INSTRUMENT (15.0 points)

The PHOENIX LIDAR instrument operated at a wavelength of 532 nm for the analysis conducted and described in the accompanying Whiteway et al. paper.

4) Construct an equation that describes the intensity of emitted LIDAR flux that the LIDAR would receive (measure) back as scattered flux from the bottom 50 meters (2.95-3.00 km altitude range) of the upper cloud indicated in Figure 1B. Describe the terms you include in your equation. Assume that there are no instrumental problems to worry about. **[7.5 points]**

Received Flux = (emitted flux minus Attenuation between the sfc and 2.75-2.8 km) times (the backscatter coefficient of cloud particles between 2.75-2.80 km) times (the attenuation from 2.75 km back down to the surface) times (the spreading of the beam as it traverses from the sfc to 2.75 km and then back down) times the total cross-sectional area of cloud particles

Rcvd Flux = Emitted x $e^{-\tau^{(sfc-2.75km)}}$ x (cloud single scattering albedo (σ) x cloud particle number density (N (m^{-3})) x π x r_{cloud}^2 x Asymmetry parameter of cloud particles factor (Fg)) x $e^{-\tau^{(sfc-2.75km)}}$ x (0.25 mrad x 2750 m)^2

The Asymmetry factor could be, with g the Asymmetry parameter: Fg= 1 - (g + 1)/2
So: Rcvd Flux = **Emitted** x **($e^{-\tau^{(sfc-2.75km)}}$)^2** x **σ** x **N** x 50 m x **Fg** x **(0.25 mrad x 2750 m)^2**

5) **Describe** how the physical characteristics of the martian atmosphere AND the physical characteristics of the dust suspended within the atmosphere would result in a LIDAR instrument operating at a wavelength of 15 micrometers being a **BAD CHOICE** for conducting the scientific investigation described in the accompanying Whiteway et al. paper. [**7.5 points**]

The martian atmosphere is primarily composed of carbon dioxide gas. CO_2 has a very strong rotational/vibrational fundamental band at ~15 μm. Thus, 15 μm flux does not penetrate very far through the martian atmosphere before being absorbed and then reemitted. So, a 15 μm LIDAR would not provide a signal that could penetrate very far up in to Mars' atmosphere, and the returned signal would be overwhelmed by the emission from the atmosphere itself and would not represent reflected flux from aerosols.

Additionally, since the dust particles are small (micron-sized), at 15 μm wavelength they will be approaching Rayleigh scattering (the size parameter for 1 micron sized dust at a wavelength of 15 μm is 0.4); the Mie regime which applies for a wavelength of 0.532 μm affords the likelihood of a different backscatter component/magnitude

SECTION III: THE MARS ENVIRONMENT EXPERIENCED BY THE PHOENIX LANDER (22.5 points)

6) On page 69 of the paper, the authors indicate that they estimate the column water ice cloud mass to amount to 1.9 g m^{-2}. **Quantitatively demonstrate** that it is appropriate that the paper does not focus on the thermodynamic (temperature) effects of this condensing (actually, deposition, since temperatures are below freezing) and subliming water upon the thermal state of the martian atmosphere. Such water condensation/evaporation processes are important within Earth's atmosphere. [**7.5 points**]

Each column of atmosphere is determined to possess only 1.9 grams of condensing/subliming water per square meter. Thus, within each square meter of atmosphere (and we can limit the vertical extent to just the sfc to 4 km), the total quantity of thermal energy liberated by the condensation of 1.9 grams of water is:

$0.0019 \text{ kg} \times (2.5 \times 10^6 \text{ J kg}^{-1} + 3.3 \times 10^5 \text{ J kg}^{-1}) = 5377$ Joules per square meter column

The quantity of CO_2 in a 1–meter square column extending from the sfc (840 Pa) to 4 km (at a pressure of ~530 Pa) is: $(849 \text{ Pa} - 530 \text{ Pa}) / 3.72 \text{ m s}^{-2} = 85$ kg of CO_2

The amount of energy required to raise the temperature of 85 kg of CO_2 by 1 Kelvin = 85 kg x 735 J kg^{-1} K^{-1} = 64,248 J, which is more than 10 times the amount of energy liberated by the condensation of 1.9 grams of water per square meter column.. so, the condensation would only provide ~ 0.1 Kelvin of CO_2 warming which is inconsequential at the scales of interest.

7) Describe how the atmospheric thermodynamic conditions (atmospheric temperature and frost temperature) indicated in Figure 1C for the 5 AM time period are physically consistent with the vertical profile of extinction indicated in Figure 1B. **[7.5 points]**

The frost point temperature profile provides a measure of the quantity of water vapor present as a function of height; a greater (warmer) frost point temperature indicates a greater local abundance of water vapor (less cooling required to achieve local saturation).

At those locations (heights) where the atmospheric temperature is below the frost point temperature, water vapor is saturated and condensation occurs. In this situation, because temperatures are well below freezing, the process will be deposition and not condensation.

Those elevations ate which the difference between the frost point temperature and the atmospheric temperature difference in greatest will be altitudes that possess the greatest number of cloud particles, so those altitudes are where one can expect the greatest cloud extinction in the units used in this paper. Vertical offsets of this correlation could be due to precipitating (falling) particles.

8) Under current conditions, liquid water is not stable on Mars' surface.

a) Discuss if it is physically (but probably not realistically) possible to change Mars' solid surface characteristics to enable Mars' equilibrium temperature to increase to the point where liquid water could be thermally stable on Mars' surface. **[5.0 points]**

b) Then, discuss a major atmospheric physical characteristic that would make it difficult for Mars' surface environment to sustain liquid water on the surface even if surface temperatures were sufficiently warmed due to changed solid surface characteristics. **[2.5 points]**

Mars' surface could potentially be 'darkened' (its Bond albedo reduced to zero, so that all solar flux is absorbed); this would maximize Mars' equilibrium temperature. The change from a Bond albedo of 0.16 to zero would not, however, provide enough additional absorbed energy to raise Mars' temperature to 273 Kelvin (in fact, the maximum value of Mars' equilibrium temperature is 226K). A calculation of this fact is best, but a strong qualitative discussion is fine, too.

Even if Mars' equilibrium temperature could be increased toward 273 K by changing surface properties (Bond albdeo), we would still be left with the situation that the surface pressure on the global average is still only 610 Pascals, which is right at the triple point of water, thus this physical situation alone would make it difficult/prohibit liquid water from existing.

The addition of significant quantities of salt to the water could reduce its melting point below the current thermal and triple-point conditions on Mars. There is some speculation that some observed 'moving and shape evolving pieces of ice' could in fact have been liquid water.