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Airglow and the Physics of Upper Atmospheres

Space spectroscopy of faint atmospheric emissions is opening a new area of planetary astronomy.

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On any clear night, away from the interference of city lights, moonlight, aurora, and so forth, the observer accustomed to the dark may readily detect a faint, diffuse glow covering the sky. Trees and buildings are silhouetted against it. Generally regarded as a nuisance by astronomers, since it limits observations on faint celestial objects, this light of the night sky originates partly from the mass of stars (including the Milky Way) that are unresolved by the eye, partly from the zodiacal light, and partly from starlight that has been scattered or diffused by passage through the atmosphere.

In addition to the contribution from these astronomical sources, a major portion of the light of the night sky arises from atomic and molecular reactions occurring at altitudes of 70 to 350 kilometers—in the rarefied atmosphere that is irradiated in the day by intense ultraviolet rays from the sun. The "airglow," as this terrestrial component was named by the late Otto Struve, itself arises from many different reactions, not all of which are well understood.

The spectrum of the night airglow is composed mostly of various atomic lines and molecular bands (see Fig. 1). Atomic and molecular oxygen (O and O_2) are both major constituents of the upper atmosphere. Molecular dissociation and electron removal in the daytime are followed by reassociation and recombination, which continue throughout the night, accompanied by emission of radiation from oxygen. Similarly, the hydroxyl radical (OH) emits bands very strongly in the infrared (but only weakly in the visual spectrum), probably as part of a photochemical cycle involving hydrogen and oxygen. Only a small portion of the spectrum is "continuous"—that is, without line structure. This continuum (thought to be emitted in the photochemical cycle of nitrogen oxides) occurs in the green, and even dominates that spectral region; it is the principal emission seen by the eye.

It is difficult to say exactly when the existence of the airglow was first recognized. With a pocket-sized spectroscope one can see the green line of atomic oxygen at 5577 angstroms, and as early as 1868 Ångström detected it in the night sky. But it was not obvious that the emission was terrestrial. Without the scattering of light in the lower atmosphere, an extended astronomical source would show no enhancement in brightness toward the horizon, whereas a source in the earth's upper atmosphere would, because of the increased thickness of the emitting shell along an oblique line of sight. Actually this effect is greatly confused by molecular (Rayleigh) scattering near the ground, but, with a good horizon and a clear sky, an observer will note some difference between the brightness at the zenith and that near the horizon. In 1906 G. J. Burns cited this effect in support of the view that the emission has a terrestrial origin, but it remained for L. Yntema, in his thesis at the University of Groningen in 1909, to rule out the possibility that scattered starlight might explain the brightening near the horizon (*1*).

In any event, quantitative ground-based photometry of the zenith-horizon effect and rocket flights into the emitting layers of the atmosphere have established the source of both the green line and the green continuum in a shell between about 90 and 105 kilometers above the earth's surface. It would have been very surprising had this glow, perceptible even from the ground, not been noticed by the astronauts, with the considerably greater brightness afforded by their seeing the shell tangentially (*2*).

As I have already indicated, the night airglow arises from a variety of reactions, and the different emissions originate from rather different height regions. When the specific reaction for an emission has become understood, it has sometimes been possible to learn, from the brightness and its variations, something of the general physics and chemistry of the atmosphere. The problems presented are different for each atomic or molecular species, and even for different lines or band systems of a single constituent. Hence, a wide variety of atmospheric physics becomes associated with airglow. In this article I can do little more than indicate some of the recent advances that show great promise for the future.

Sunlit Airglow and the Ionosphere

In his George Darwin lecture to the Royal Astronomical Society in 1933, V. M. Slipher briefly noted the presence in twilight of an emission that was absent or at least much weaker at night.

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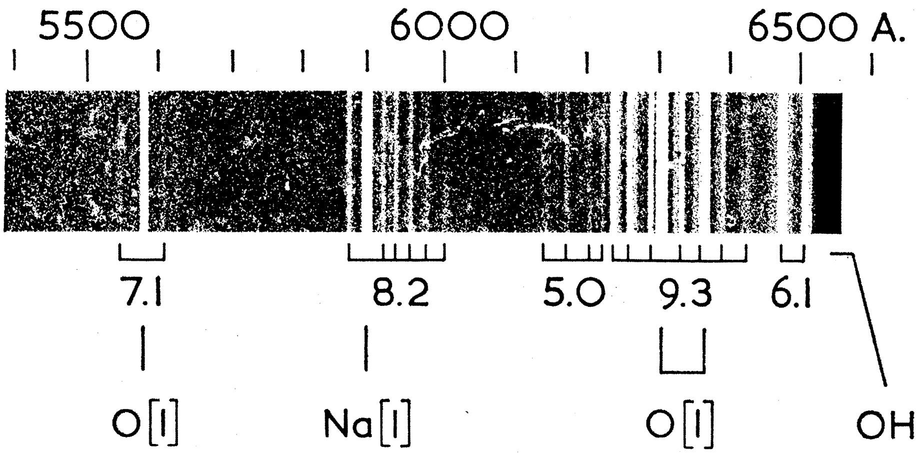

Fig. 1. Spectrum of the night airglow in the green and red regions at low dispersion (65 Å/mm on the original plate). The strong lines arise from oxygen at 5577, 6300, and 6364 angstroms and from sodium at 5893 angstroms. The other features are due to the OH vibration-rotation spectrum; the numbers below the spectrum give the vibrational quantum numbers for the various bands. [Spectrum obtained by D. E. Blackwell, M. F. Ingham, and H. Rundle; reproduced courtesy University of Chicago Press]

This was the violet band of N_2^+ at 3914 angstroms, arising from the scattering of violet sunlight by molecular ions in the earth's ionosphere. The ionosphere is the region, above 90 kilometers or so, in which a small fraction of the atoms and molecules have an electron removed by far-ultraviolet light and x-rays from the sun. Even this small abundance of free ions and electrons is sufficient to govern the propagation of terrestrial radio waves. Thus, N_2^+ is a minor, but important, constituent of the upper atmosphere. Similarly, atomic sodium (Na) is very rare in the atmosphere, but the familiar yellow "D lines" have a twilight enhancement that has been widely studied. Several other twilight emissions have been discovered and extensively observed; as with the nightglow, each one has its own particular charms, and some are more amenable to physical analysis than others.

With the advent of rockets in atmospheric research, serious efforts were directed toward observing and predicting spectral emissions in the daytime sky. Rockets have been used for two reasons: They provide a means of observing in the ultraviolet, which is screened from the ground by the absorbing atmosphere, and of avoiding the strong Rayleigh scattering of sunlight, which at the ground overwhelms the weak airglow. In spite of this second factor, however, two ingenious ground-based techniques have been successfully used for studying the "D lines" of sodium and the red lines of oxygen, respectively (*3*).

In order to emphasize the role that these studies may play in atmospheric physics, I shall concentrate this discussion on a topic of considerable current activity: the airglow and the ionosphere. Ionospheric soundings by reflected radio waves yield data on the amount of ionization at a given height but give no information on the important question of the proportion of ions in different constituents (for example, O_2^+, O^+, N_2^+). Mass spectrometers flown into the ionosphere on a few occasions have sampled the ionic abundances in the environs of the rockets. Airglow, on the other hand, provides a means of deriving abundances over the entire line of sight above the rocket. The feasibility of using this technique to obtain abundances of N_2^+ has recently been demonstrated by L. Wallace, who was the first to measure the violet N_2^+ band system in the day airglow.

Another potential use of day airglow in ionospheric studies is its use for direct measurement of the rate of ion-electron recombination. Again, conventional radio soundings measure only the rate at which the electron density changes; they are not able to disentangle directly two or more distinct recombination processes. Thus, the red lines of oxygen, which have now been detected by several techniques, are thought to arise in part from a recombination mechanism important in the higher region of the ionosphere (the *F* region). Moreover, Wallace's spectrometer flight disclosed two other emissions (a nitrogen line at 5199 Å and the green line of oxygen at 5577Å) that probably arise from two additional recombination processes. (The much weaker appearance of the green line at night is due to an entirely different process; the daytime recombination mechanism is not expected to be important at night.) These various recombination emissions should have quite different dependences on height and time of day. The systematic application of these various new techniques, in conjunction with the conventional ionospheric soundings, appears to hold great promise (*4*).

Ionospheric theory requires a good knowledge of the neutral atmosphere, both for computing the rate of ionization from a known solar flux and for deciphering the spectroscopic data on the recombination rate. While satellite drag yields the total mass density, individual constituents may best be studied optically. Airglow offers a powerful tool, but it has not yet been exploited. One emission that would be particularly useful for obtaining atomic oxygen densities over a wide altitude range at several hundred kilometers is the 1302-angstrom resonance line. Preliminary measurements have been made, but only at lower altitudes where the radiative transfer problem for this emission is rather complex and densities are not so readily derived. A fluorescence line in the near-infrared, excited by the solar Lyman-β line of hydrogen, might be equally valuable in this respect and does not offer the complications of the resonance transition (*5*).

The Hydrogen Geocorona

Another sunlit airglow that is opening a whole new approach to planetary physics is the radiation from the outermost atmosphere or "planetary corona," the latter term connoting a faintly glowing, as well as distended, atmosphere. A far-ultraviolet glow about the earth was first discovered in late 1955, by means of a night-time rocket flight, by H. Friedman and his associates at the Naval Research Laboratory. The radiation is at 1215 angstroms, arising from the resonance or "Lyman-α" transition of atomic hydrogen (H).

At first it seemed that the glow was interplanetary, but subsequent work has established that it does arise mainly from a geocorona of atomic hydrogen. The sun is quite bright in Lyman-α radiation, which dominates its neighborhood in the solar spectrum. The geocorona thus glows by scattering sunlight, a relatively efficient process for an atom at its resonance frequency. This mechanism is basically the same as the one producing the N_2^+ glow in twilight, the main distinction being that the N_2^+ is within 300 kilometers or so of the earth, whereas atomic hydrogen extends outward for several thousand kilometers.

The surprising thing was—and to some extent still is—that even in directions roughly opposite to the sun, where the earth's shadow also extends for thousands of kilometers, the glow was found to be almost as bright as it was over the rest of the sky, where the distant atmosphere is more fully illuminated by sunlight. Also requiring explanation is the fact that the spectral line has a width much greater than would be expected for a simple geocorona. Interpreted in terms of the Doppler effect for a relative motion between the source and the observer, the line width indicates that some 10 to 20 percent of the observed atoms have radial velocities exceeding the velocity of escape from the surface of the earth (11 km/sec). Some data on the height distribution of Lyman-α radiation are available, also, but different experimenters flying photometers at different times seem to derive different distributions of hydrogen, for reasons that are not yet clear (*6*).

Although an enormous effort has gone into observing the geocorona as revealed in Lyman-α radiation, the problems are formidable and the present state of empirical knowledge is still quite crude. As one might expect with such an exciting new discovery, it has inspired an avalanche of theoretical papers. Some of them deal with fairly fundamental problems, such as radiation scattering and atmospheric structure appropriate to a highly distended and rarefied atmosphere. Others have been concerned with developing models for fitting the various observations together to form a consistent picture.

At high altitudes—perhaps above 100 kilometers or so—the atmosphere is so rarefied that atoms of different atomic weight are not homogeneously mixed by turbulence and other circulation, as they are in lower regions. Instead, the different gases diffuse through one another so effectively that each constituent is distributed with height independently of the others. Thus, beyond a height of 1000 kilometers, hydrogen becomes the principal constituent. Moreover, the kinetic temperature rises to about 1000°K in the upper part of the ionosphere and beyond, owing to the absorption there of large amounts of ionizing solar energy. The low atomic mass and the high temperature both tend to distend the hydrogen geocorona enormously, and at very great distances the decrease in gravitational attraction also serves to make the geocorona less compact. Thus, beyond a few hundred kilometers the hydrogen density decreases very gradually with distance—by a factor of 2 or less in 1000 kilometers.

In the earth's atmosphere above about 500 kilometers, atomic collisions are so rare that the atoms rise out of lower regions in free, ballistic flight. At altitudes of about 1 earth radius and higher, the absence of deflecting collisions causes the horizontal pressure to be less than the vertical pressure; that is, the pressure is not strictly isotropic. Hence the application, above this region, of the law of hydrostatic equilibrium gives an erroneous distribution of density with height. One must therefore derive the density from a statistical orbit theory based on the Boltzmann equation for collisionless particles (*7*).

At the moment, three distinct, but not entirely independent, hypotheses for the distribution of hydrogen about the earth are being debated. (i) There is a greater concentration of hydrogen in the part of the geocorona that is on the night side, in shadow, than there is in the sunlit part. Lyman-α photons are thus scattered several times in the nighttime corona, thereby partially filling in the part that is in shadow. (ii) A portion of the Lyman-α glow at night arises from high-speed interplanetary hydrogen atoms that diffuse into the neighborhood of the sun and the earth from interstellar gas. This portion accounts for the width of the line profile and, arising from atoms far from the earth, it is present even in the direction of the shadow. (iii) The terrestrial hydrogen atoms at altitudes of several earth radii, including those (a sizable fraction) that are escaping (or "evaporating," as it were) from the main body of the upper atmosphere, are swept up by the solar gas streaming from the sun. This solar wind carries the atoms downstream, in the general direction of the earth's shadow. At large distances from the earth, these accelerated atoms are illuminated by the sun and account for the apparent filling in of the shadow as well as for the spectral width due to the Doppler effect. Multiple scattering is unimportant (*8*).

It appears that these different possibilities cannot be adequately assessed from the data now available. The problem of a model will probably, in fact, not be laid to rest until a Lyman-α photometer is flown well outside the geocorona, where it can look back at the earth with some perspective. In a way this seems a vulgar means of solution, especially to one accustomed to making the best use he can of limited types of observation, as one must do in astrophysics. And to an extent some investigators of the problem may be overemphasizing certain data relative to others, as the blind men did with the elephant. But in all fairness, there may be important variations with time of day, and there almost certainly have been variations attributable to the solar cycle during the few years in which observations have been made. It is really very difficult to sort out with confidence the proper combination of effects that influence the observational data.

Airglow of Other Planets

Spectroscopic observations offer an untapped potential for a comparative study of the upper atmospheres of the planets. Spectrometers or photometers flown past a planet might observe nighttime emissions resulting from the photochemical reactions and ionospheric recombinations peculiar to that atmosphere. The most immediate observational possibility, however, lies with the sunlit airglow, which is likely to be not only much brighter than the nightglow but more amenable to interpretation, especially if the emission arises from atomic or molecular scattering.

For example, photometry of the corona about Mars or Venus would yield directly the distribution of density with distance from the planet, and this distribution in turn constitutes a direct measure of the temperature of the planetary corona. The temperature of the upper atmosphere governs the rate of evaporation of the light elements from the planet and is therefore a necessary parameter for an understanding of the evolution of the atmosphere.

In the case of Mars, some theoretical guesses have been made, and it seems likely that an atomic-oxygen corona will be found there (the resonance line is at 1302 Å—a line also bright in the solar spectrum). For Venus, our present understanding of the chemical composition and atmospheric structure is even more rudimentary. Probably Venus's corona is cooler than the earth's, but in any case it is waiting for direct measurement (*9*).

Other sunlit airglows may also yield information on the chemical constituents of an atmosphere. However, the visible and near-infrared regions reflect the strong solar continuum, blinding the spectrometer to the relatively faint airglow. In the ultraviolet the situation is different, for a planetary atmosphere absorbs most of this light, reflecting only on certain atomic lines and molecular bands. The radiative-transfer problems associated with the formation of ultraviolet airglow in planetary atmospheres under a variety of conditions have been treated in a recent series of papers (*10*).

The far-ultraviolet spectra of Jupiter and Saturn are probably dominated by ordinary molecular (Rayleigh) scattering of the principal solar emissions, such as Lyman α. In addition, however, some of the scatterings by H_2 molecules in the upper atmosphere will involve quantum (Raman) transitions, causing the re-emitted light to be degraded toward the visual region. In a thick atmosphere the average photon experiences several scatterings, and the probability of occurrence of a Raman transition is thus increased. Brandt calculates that on Jupiter the first Raman line, located 65 angstroms from the Lyman-α line, toward longer wavelengths, will be nearly half as bright as the Lyman-α emission itself, provided that no energy is lost by atmospheric absorption. Spectrophotometric measurements would essentially test the latter assumption. Rayleigh and Raman scattering may also be important on Mars above the level of strong molecular absorption (*11*).

Summary

While many problems remain in the study of the classical night airglow, a whole new area of planetary astronomy is rapidly developing with the study of sunlit airglow. Although we must rely on space technology for the most fruitful observations, the sunlit airglows of the planets arise largely from processes that can be quantitatively understood. This happy circumstance means that airglow may serve as a tool —and I believe it will become a powerful one—for probing into the physical processes and structure characterizing the atmospheres of the planets (*12*).

References and Notes

1. I do not attempt to list complete bibliographies here but, instead, refer to the principal recent papers and to more extensive, albeit more technical, discussions that do contain thorough documentation. The spectrum of the airglow and the history of early work is discussed in J. W. Chamberlain, *Physics of the Aurora and Airglow* (Academic Press, New York, 1961), chap. 9, pp. 345–392.
2. For discussion of airglow observations by astronauts Glenn and Carpenter, see M. S. Carpenter, J. A. O'Keefe III, L. Dunkelman, *Science* **138**, 978 (1962); M. J. Koomen, I. S. Gulledge, D. M. Packer, R. Tousey, *ibid.* **140**, 1087 (1963).
3. The classical work on twilight is treated in J. W. Chamberlain, *Physics of the Aurora and Airglow* (Academic Press, New York, 1961). The daytime emission of sodium ions has been studied with a sodium absorption cell, which acts as a high-resolution filter, by J. E. Blamont and T. M. Donahue [*J. Geophys. Res.* **66**, 1407 (1961)]. The oxygen lines have been observed, with the aid of a polarimeter that rejects Rayleigh-scattered light, by J. F. Noxon and R. M. Goody [*J. Atmospheric Sci.* **4**, 342 (1962)]. I have summarized the different physical categories of daytime airglow and additional observational and theoretical literature on specific emissions in *J. Quant. Spectr. Radiative Transfer*, in press.
4. The red line of oxygen has been observed photographically with a balloon-borne spectrograph by L. Wallace [*J. Geophys. Res.* **68**, 1559 (1963)], and with rocket-borne photoelectric photometers with narrow-band filters by E. C. Zipf and W. G. Fastie (*ibid.*, in press). Measurements have been obtained with a photoelectric spectrometer aboard a rocket for N_2^+ (at 3914 Å and other wavelengths), for oxygen (at 5577 Å), and for nitrogen (at 5199 Å) by L. Wallace and R. A. Nidey (*ibid.*, in press).
5. The resonance line of oxygen at 1302 Å was detected in the terrestrial daytime airglow by T. A. Chubb, E. T. Byram, H. Friedman, and J. E. Kupperian, Jr. [*Ann. Geophys.* **14**, 109 (1958)], and it has been studied more recently by T. M. Donahue and W. G. Fastie (*Proc. Intern. Space Sci. Symp. 4th, Warsaw, 1963*, in press). The theory of the 8446-Å emission of oxygen has been developed by J. C. Brandt [*Astrophys. J.* **130**, 228 (1959)].
6. The various Naval Research Laboratory observations on Lyman-α emission in the night sky have been summarized by T. A. Chubb and E. T. Byram, in *Space Research III*, W. Priester, Ed. (North-Holland, Amsterdam, 1963), p. 1046. Other observations have been reported by D. F. Heath and W. G. Fastie [*Trans. Am. Geophys. Union* **43**, 435 (1962)] and by T. M. Donahue and W. G. Fastie (*Proc. Intern. Space Sci. Symp. 4th, Warsaw, 1963*, in press).
7. The statistical orbit theory was first applied in this context independently, and with rather different approaches, by E. J. Opik and S. F. Singer [*Phys. Fluids* **2**, 653 (1959); *ibid.* **4**, 221 (1961)], F. S. Johnson and R. A. Fish [*Astrophys. J.* **131**, 502 (1960)], F. S. Johnson [*ibid.* **133**, 701 (1961)], and J. W. Chamberlain [*ibid.* **131**, 47 (1960)]. I have recently extended the theory considerably in a paper [*Planetary Space Sci.* **11**, 901 (1963)] containing a bibliography of the literature on the outer fringes of an atmosphere. This literature extends back to 1846, the topic having originated simultaneously with the kinetic theory itself.
8. The word *geocorona* in this context was introduced by I. S. Shklovsky [*Planetary Space Sci.* **1**, 63 (1959)]. The first serious advocate of a geocoronal, rather than a primarily interplanetary, origin of the Lyman-α glow was F. S. Johnson (see *7*), who argued that the multiple scattering of Lyman-α radiation would be sufficient to explain the intensity distribution over the night hemisphere. Hypothesis i, which is an extension of this idea, was proposed by T. M. Donahue [*Space Sci. Rev.* **1**, 135 (1962); *J. Geophys. Res.*, in press]. Hypothesis ii, also an extension of Johnson's work, was proposed by T. N. L. Patterson, F. S. Johnson, and W. B. Hanson [*Planetary Space Sci.* **11**, 767 (1963)]. Hypothesis iii (the "geocoma" hypothesis) is a modification that was proposed by J. C. Brandt [*Astrophys. J.* **134**, 394 (1961); *Nature* **195**, 894 (1962)]. Actually there is much interdependence in this work, and the reader should realize that my classification into three separate hypotheses is something of an oversimplification.
9. I have completed a tentative model for the upper atmosphere of Mars [*Astrophys. J.* **136**, 582 (1962)]. Recently I discussed coronal emissions from other planets more fully in *Planetary Space Sci.* **11**, 901 (1963).
10. J. W. Chamberlain, in *The Atmospheres of Mars and Venus*, W. W. Kellogg and C. Sagan, Eds. (National Academy of Sciences, Washington, 1961), p. 147; ——— and Y. Sobouti, *Astrophys. J.* **135**, 925 (1962); Y. Sobouti, *ibid.*, p. 938; ———, *ibid.* **138**, 720 (1963); ———, *ibid.*, p. 748; ———, *Astrophys. J. Suppl. Ser.* **7**, 411 (1963).
11. J. C. Brandt, *Mem. Soc. Roy. Sci. Liege* **7** **(1962)** 137 (1962); *Planetary Space Sci.* **11**, 725 (1963).
12. This article is contribution No. 41 of the Kitt Peak National Observatory. The observatory is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.