Reports

Lancefield Swamp and the Extinction of the Australian Megafauna

Abstract. *Excavations into the Australian swamp of Lancefield show that a bone bed dated at 26,000 years ago contains perhaps 10,000 giant extinct animals. Associated artifacts suggest that humans were in the area, but the direct cause of death of the animals is, on present evidence, not explicable. Such a recent date for the classic megafauna shows that it was living together with humans for at least 7000 years in southeast Australia. This enduring association argues against a catastrophic and rapid overkill in the Australian Pleistocene.*

How did late Pleistocene humans behave when first confronting the continental faunas of the Americas and Australia? Were some species hunted to extinction, or was their disappearance at the end of the Pleistocene caused by climatic change? There have been some challenging narratives (*1*), all of which have an unfortunately deficient foundation of accurate absolute dates.

Dating the extinction of the Australian Pleistocene megafauna has been a particular problem (*2*). Fieldwork over the last 10 years has encouraged two opinions—that either the time of major extinction was before humans arrived or it was soon after. Radiocarbon dates from the Willandra Lakes of southern New South Wales demonstrate the presence of humans in Australia more than 33,000 years ago, but no archeological site has satisfactorily shown any prolonged overlap of humans and classic megafauna (*3*).

One probable source of confusion has been that important Pleistocene archeological sites (such as Mungo and Koonalda Cave) have yielded meager biological data. Claims that other sites have dated the megafauna have, in general, proved to be equivocal. In any case, no site has combined artifacts, an abundance of bones of extinct species, clear stratification, and radiocarbon dates on charcoal.

Recent excavations at a small swamp at Lancefield have put a sharper focus on the time of extinctions. The swamp has a 0.2-m-thick bone bed, 1.5 m below the surface. From this bone bed have come the well-preserved remains of six extinct megafaunal species, in a datable stratigraphy. The age of 26,000 years shows that these species and humans had been living contemporaneously in southeast Australia for at least 7000 years.

The swamp is on the southwest edge of the small agricultural town of Lancefield, 37°16′S, 144°44′E. It is in a depression in a grassy plain developed on about 3.5 m of an alluvial clay overlying Pliocene basalts. The top of the clay has a laterite cap. At the head of a minor drainage line a spring emerges from under this cap. The spring has undercut the cap and eroded a small amphitheater (80 m across), in which the swamp has formed. The surrounding catchment is limited to an area little greater than that of the swamp itself.

A cross section through the swamp shows several phases of downcutting by the spring waters, producing an upper terrace and a swamp floor or lower terrace, into which a narrow channel was finally incised. The downcutting removed the laterite cap so that the underlying clay (the green clay) now forms the base of the swamp. At about 26,000 years ago this erosion stopped and some 1.7 m of swamp sediment began to be deposited.

We explain the change from erosion to deposition at 26,000 years by a major decrease in spring flow. It is significant that a major hydrologic change was previously recorded from other places in southeast Australia at about this time (*3*).

The units of sedimentation are illustrated in Fig. 1 and discussed below.

0036-8075/78/0602-1044$01.00/0 Copyright © 1978 AAAS

Unit V. The basal green clay. The high water table within the swamp has caused gleization on the basal green clays underlying the sediments. Gleization is most intense beneath the swamp floor, where the more clastic overlying sediments provide an aquifer for groundwater flow through the swamp. At the edge of the swamp the basal clays change to mottled gray and brown in the oxidizing zone beneath the laterite.

Unit IVb. Filling of the swamp began ~ 26,000 years ago (see below for details of dating) with the backfilling of the small channel which previously drained the spring. The gravelly clay of the channel fill is the coarsest sediment in the swamp. Quartz is the dominant clastic material. Whole bones, bone fragments, and charcoal are common.

Unit IVa. Following the overtopping of the channel, the ~ 0.2-m-thick bone bed was deposited across the lower terrace. The bones interlock as a horizontal network, in a matrix of greenish gray to black clay and gravelly clay. Laterite fragments and pellets are the dominant clastic materials.

The bones are limited to an area of approximately 2000 m^2, fanning out from the spring head. Downswamp, the bone bed cuts out sharply against a slight rise in the base clay beyond which, for a few meters, the delicate shells of unerupted *Macropus titan* molar teeth are found. This indicates that water controlled the local distribution of bones, a conclusion which is confirmed by localized evidence of preferred orientation of long bones. Important factors in the preservation of the bones have been the constant saturation imposed by the spring and the alkaline *p*H of its waters.

Unit III. The bone bed is overlain, probably disconformably, by ~ 0.12 m of a black mottled clay, which contains occasional pebbles, quartz grains, laterite pellets, and eroded bone fragments. The bones seem to be reworked from the bone bed. The mottled clay is also restricted to the area of the lower terrace.

Unit II. The mottled clay is overlain by ~ 0.7 m of a black clay, which occurs throughout the swamp. It contains almost no bone fragments. The presence of a floor of geometric microliths near its base indicates a Holocene age of less than 6000 years (*4*).

Unit I. The topmost unit is ~ 0.7 m of brown clay, which contains European artifacts. It formed rapidly after the surrounding land was cleared and the swamp's outlet dammed.

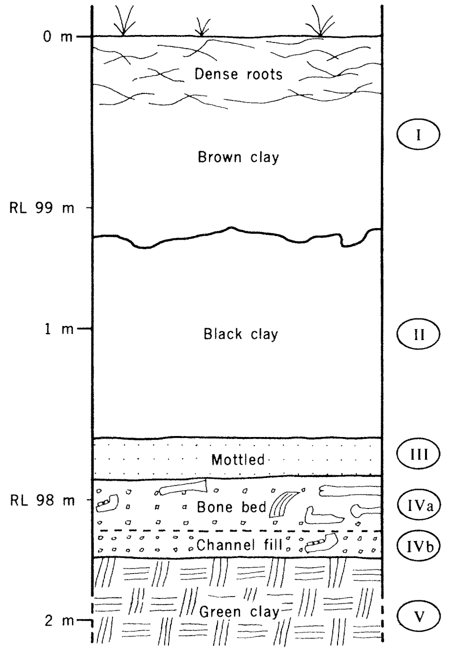

Fig. 1. Section of the south face of the 1977 excavation. The SUA-685 date of 26,600 ± 650 years ago is from the channel fill.

Figure 2 shows selected pollen taxa, divided into the four zones L1 through L4. These zones are well correlated with the sedimentary units, although zone L1 overlaps the bone bed and mottled clay, with no indication of a pollen division.

Plants of aquatic or wet habits (*Triglochin* and *Lemna*) indicate that during L1 (the bone bed and mottled clay) free water occupied the site, at least seasonally. However, the low Myrtaceae values suggest that the surrounding plains were virtually treeless. In Victoria the limiting rainfall for tree growth on soils similar to those around Lancefield is slightly less than 500 mm/year. So the annual rainfall at Lancefield during L1 may have been at least 200 mm less than today's 700 mm.

During L2 (the base of the black clay) *Leptospermum* grew, probably as a thicket or heath confined to the shallow depression over the bone bed. The increased Myrtaceae pollen indicates that eucalypts were now growing on the plains around the swamp, forming a grassy woodland.

In zone L3 (the black clay) the increasing Cyperaceae pollen shows the development of a sedge swamp, reflecting a climate similar to that of today.

In zone L4 (the brown clay) the decrease in Cyperaceae and the increase of Polygonaceae pollen probably reflect European activity. *Salix* certainly does.

The bones consist of calcium phosphate, with no residual collagen or secondary mineralization to give them strength. Nevertheless they are in good condition. They show very little cracking, abrasion, or surface flaking, which suggests that after the death of the animals their bones did not lie exposed for long on dry land, that they were not carried far by water, and that they were constantly covered by water after deposition. In all cases where it is possible to recognize bones from a single individual these are found within a meter or so of each other. Some of the bones (but less than 0.35 percent) show the toothmarks of the extinct marsupial phalanger *Thylacoleo*.

However, in spite of their good condition the bones are not found in articulation, they have settled horizontally, many which are broken were broken be-

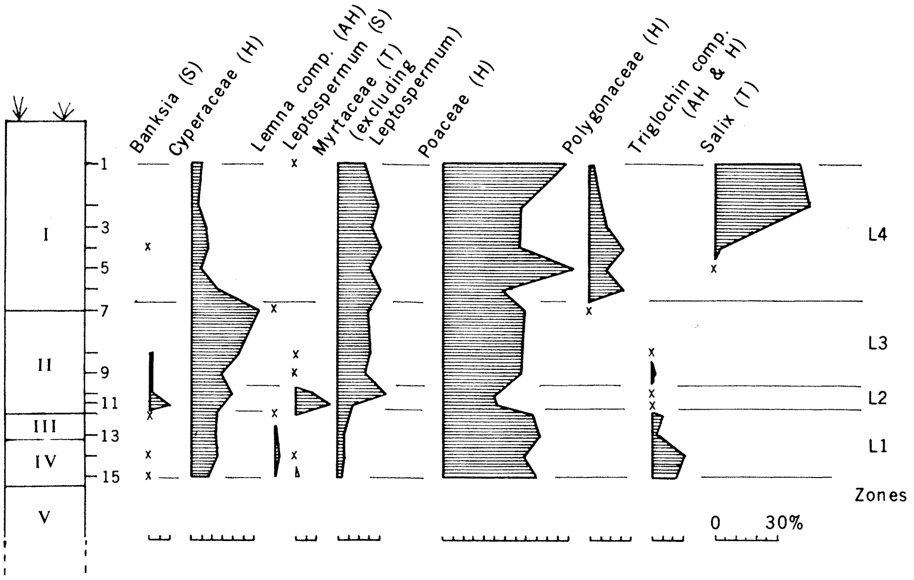

Fig. 2. Selected pollen taxa. The sedimentary units and pollen samples are identified on the left. Abbreviations: *T*, tree; *S*, shrub; *H*, herb; and *AH*, aquatic herb.

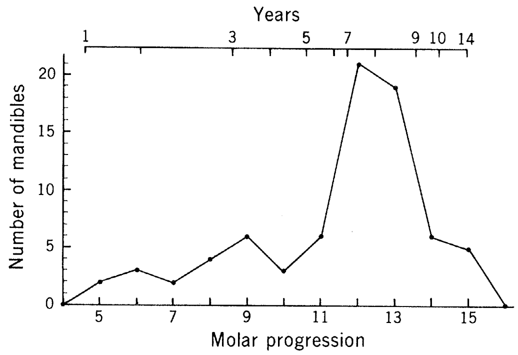

Fig. 3. Age in years of the fossil *Macropus titan* mandibles, based on molar progression in the living *M. giganteus*. The method is to assign sequential numbers to three points on each molar tooth in its row (for instance, M_1 has numbers 1 to 3 and M_2 numbers 4 to 6). Age is determined by observing which point is opposite the angle on the jaw formed by the upper edge of the ramus and the anterior edge of the coronoid process.

fore final deposition, and no complete skulls are found. There is some evidence for slight water sorting—the distribution of the smaller bones is slightly different from that of the larger bones, there are localized examples of long bones tending to have preferred orientations, and unerupted tooth caps have been carried marginally beyond the limits of the bone bed. However, the sorting effects are not pronounced; in all areas sampled there are small bones of the megafauna (for instance, phalanges).

All this suggests that partial carcasses and broken bones accumulated in the swamp, and that some slight movement occurred after the ligaments had decayed and before the bones finally settled close to where they had originally been deposited.

The limits of the bone bed have been defined by several sampling excavations, and its contents are remarkably homogeneous. The 1975 excavation of 5 m^2 yielded some 3000 bones, representing a minimum number of individuals of 72 for all species. By extrapolation to the whole bone bed, and taking into account differential density, we estimate that more than 10,000 individuals are represented in the swamp.

The approximate frequencies of the species in the bone bed are:

Macropus titan	90 percent
Protemnodon anak	7 percent
Protemnodon cf. *brehus*	< 1 percent
Sthenurus occidentalis	< 1 percent
Diprotodon sp.	< 1 percent
cf. *Genyornis* (*5*)	< 1 percent
Dromaius sp. (emu)	< 1 percent

Except for *Dromaius*, they are all extinct. They are all large species; *M. titan* is twice the mass of the living gray kangaroo (*M. giganteus*) and the smallest (*S. occidentalis*) is about the size of a modern kangaroo.

Although the large bones of smaller species are absent, we do find the small bones of the megafauna. For example, the minimum number of individuals of *M. titan* (in a sample of the 1975 excavation) based on mandibles is 37; on the astragalus, 10; on the calcaneum, 19; and on the cuboid, 13. The absence of teeth of smaller species refutes any ad hoc explanation that the bones of small animals have differentially decayed. We are not faced with the biased result of some postmortem sorting process. This remarkably restricted species list, of large species only, shows that some special selective event was causing death.

The age at death of the *M. titan* remains has been reconstructed by using aging parameters based on the modern gray kangaroo's molar progression (Fig. 3). Eighty percent of the *M. titan* sample was over 7 years old, and 92 percent was more than 2 years old. To eliminate the possible effect of differential destruction of juvenile mandibles the isolated teeth were also analyzed; their statistics confirm the scarcity of juveniles. Thus Fig. 3 suggests a population having very few young animals, such as has been observed in modern herds, when breeding ceases after several years of drought (*6*). Alternatively, only the mature animals from a normal population were dying.

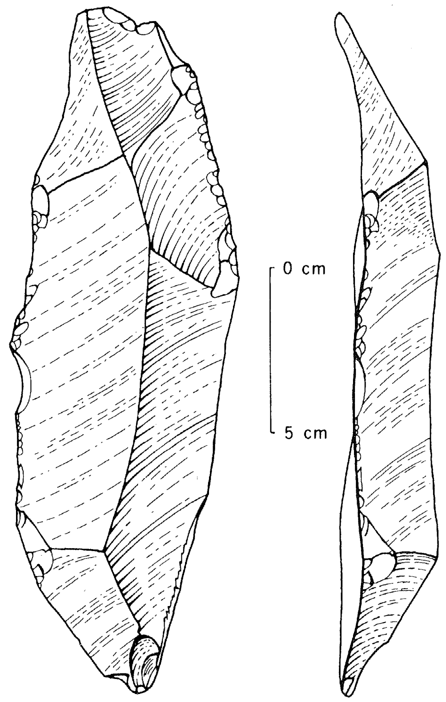

Fig. 4. Quartzite blade from the bone bed (sample NMV/X 80515).

The sex ratio in the sample, estimated from bimodal distributions of shape in the metatarsals, is one male to three females. In modern gray kangaroo populations there is normally only a slight excess of females over males, but among red kangaroos sex ratios similar to those at Lancefield have been observed (*7*).

About 7.5 percent of the bones show disease. It is impossible to decide whether this incidence is high or low because there are insufficient studies of disease among wild macropodids. The commonest disease at Lancefield is "lumpy jaw," which has been seen in wild animals during drought (*8*).

In the underlying channel fill a new factor is evident, even though the volume of channel fill screened is less than 25 percent of that of the bone bed screened. In the same condition as in the overlying bone bed are the same megafaunal species, represented by jaws, postcranial bones, and fragments. In addition, there are isolated teeth of smaller species never found in the bone bed, namely: *Sarcophilus* sp. (Tasmanian devil; extinct on the mainland), *Thylacinus* cf. *cynocephalus* (Tasmanian wolf; extinct on the mainland), *Aepyprymnus rufescens* (rufous rat kangaroo), *Propleopus* sp. (extinct), cf. *Thylogale* (pademelon), *Vombatus* sp. (wombat), *Macropus* cf. *rufogriseus* (red-necked wallaby), *Macropus* cf. *dorsalis* (black-striped wallaby) (there may be only one individual present of each of the preceding taxa), *Mastacomys fuscus* (broad-toothed rat) (*9*), and Muridae gen. et sp. indet. (*9*).

It seems that we have the results of two different processes in the channel fill. There are the small animals which died and disintegrated on the edge of the swamp and whose surviving teeth were washed into the channel fill. In addition there are better preserved remains of those megafaunal species which are also found in the main bone bed.

Although we are agreed that the selection for size in the bone bed reflects selection at the time of death, we disagree about the emphasis that should be given to alternative explanations for the deaths. The various explanations will be examined in separate publications (*10*). Those we wish to foreshadow now are:

1) Recurrent droughts, forcing large species to congregate around a source of permanent water; limited in how far they could move, because of their depen-

dence on water, the large numbers of individuals rapidly ate out the available food near the swamp and died (*11*).

2) *Thylacoleo* (whose predatory habits are otherwise unknown) was using the swamp for an ambush, its behavior programmed to kill large mammals, from which it ate mainly the flesh.

3) Humans were using the swamp for an ambush or the focus of drives. The meat was being cut off the undismembered carcasses, on which *Thylacoleo* occasionally scavenged.

In 1974, during a paleontological excavation, a large quartzite blade (NMV/X 80515) was found by one of us (P.G.M.) in section and firmly embedded in the bone bed (Fig. 4). In 1977, while screening channel fill for teeth and charcoal, we found a 3-cm^2 piece of a flake (NMV/X 80516) made of the same quartzite as the original blade. Although 191 artifacts have been found in the overlying black clay, none of them is made of this rock type. These two artifacts indicate that humans visited the swamp at the time the bone bed was being formed.

The scarcity of artifacts in the channel fill might suggest that the catchment of the swamp was not a place of regular human habitation 26,000 years ago. Yet this interpretation is problematical because although the present-day surface soils of the swamp's catchment are rich in artifacts of the Holocene small tool tradition, none was found in the washed in (since A.D. 1830) accumulation of the brown clay.

In Table 1 we list all the radiocarbon dates available, all of which, except for the charcoal dates, must be taken as minimum ages for their respective sedimentary units. We could not recover a datable amount of charcoal from the bone bed, but we have established its maximum age by dating the underlying channel fill. In 1976 the channel fill was found, for the first time, in part of a 2 by 1 m excavation in the southwest part of the swamp, but not in direct stratigraphic relation to the bone bed. It was dated by sample SUA-538 at 26,000 ± 650 years. In 1977, in an extension of this excavation, we found the bone bed overlying this channel fill. Here the underlying channel fill was dated by sample SUA-685 at 25,200 ± 800 years, not significantly different from the date for SUA-538.

Because our knowledge of the absolute age of the bone bed depends on the charcoal dates SUA-538 and SUA-685, from the channel fill, our reliance on these two charcoal dates needs some justification.

Table 1. Radiocarbon dates for Lancefield swamp material.

Sediment unit	Material dated	Laboratory number	Age (years ago)
Black clay	Soil organic matter: acid- and alkali-insoluble	SUA-425A	1,915 ± 110
Black clay	Soil organic matter: alkali-soluble	SUA-425B	1,735 ± 120
Bone bed	Bones—free carbonate	GX-4118C	3,100 ± 210*
Bone bed	Bones—acid- and alkali-insoluble residue	GX-4118R	8,775 ± 260
Bone bed	Bones—acid- and alkali-insoluble residue	SUA-407R	12,550 ± 650†
Bone bed	Bones—bone apatite	SUA-407A	16,070 ± 315
Bone bed	Bones—bone apatite	GX-4118A	19,800 + 450‡
Channel fill	Charcoal	SUA-685	25,200 ± 800
Channel fill	Charcoal	SUA-538	26,600 ± 650
Green clay	Plant remains	SUA-453	Modern§

*Identical $\delta^{13}C$ values for free carbonate and apatite suggest that apatite dates have been reduced by exchange with groundwater carbonate. †Tests for collagen were negative. ‡Material dated after prolonged pretreatment with acetic acid. §113.9 ± 2.4 percent modern; it was dated on the off-chance that the remains were fossil roots.

The charcoal fragments, which are of robust structure, are the broken pieces (up to 10 mm long) of "twigs" which were in life some 2 mm in diameter. A spiky superficial anatomy is still preserved, but they have defied botanical identification. During excavation these fragments were seen to be distributed throughout the channel fill, with minute fragments of the same type grading up into the bone bed. This highly distinctive charcoal has never been found in the overlying clays. Thus the form and distribution of this charcoal argue for a deposition contemporary with the channel fill and against any downward intrusion in later times.

Because this charcoal has survived in such a robust and crunchy form, it has been possible to rigorously treat it before combustion. After hand-picking of rootlets, it was boiled in dilute phosphoric acid, washed in distilled water, soaked for 24 hours in alkali-phosphate solution (specifically to remove any humic acid contaminants), washed, reboiled in acid, and washed (*12*).

A final safeguard is that the two samples, which gave dates not significantly different from each other, were collected in different places in different years.

We conclude therefore that the bone bed is the same age as or younger than the channel fill, whose two dates average 26,000 ± 500 years. We are confident that we now have reliable absolute age brackets for the Lancefield bone bed. The extreme younger bracket is set by sample GX-4118A at 19,800 ± 450 years, but we incline to the view that the bone bed and channel fill represent roughly contemporary depositional events ~ 26,000 years ago.

Finally, we conclude that Lancefield swamp, considering the dates for early humans elsewhere in southeast Australia, shows that humans and several species of megafauna were living together for at least 7000 years. Such a prolonged coexistence calls into question the model of rapid overkill proposed by Jones (*13*) for Australia, a model which is analogous to that proposed by Martin (*1*) for the Americas.

R. Gillespie
Radiocarbon Dating Laboratory,
Department of Physical Chemistry,
University of Sydney,
Sydney, New South Wales 2006
D. R. Horton
Australian Institute of Aboriginal
Studies, Canberra City, Australian
Capital Territory 2601
P. Ladd
Department of Botany, University of
Melbourne, Parkville, Victoria 3052
P. G. Macumber
Victorian Department of Minerals and
Energy, Melbourne, Victoria 3000
T. H. Rich
National Museum of Victoria,
Melbourne 3000
R. Thorne
State Rivers and Water Supply
Commission, Armadale, Victoria 3143
R. V. S. Wright
Department of Anthropology,
University of Sydney,
Sydney 2006

References and Notes

1. P. S. Martin, *Science* **179**, 969 (1973).
2. For recent reviews, see J. J. Calaby, in *The Origin of the Australians*, R. L. Kirk and A. G. Thorne, Eds. (Australian Institute of Aboriginal Studies, Canberra, 1976), p. 23; S. Bowdler, in *Sunda and Sahul*, J. Allen, J. Golson, R. Jones, Eds. (Academic Press, London, 1977), p. 205.
3. J. M. Bowler, in *The Origin of the Australians*, R. L. Kirk and A. G. Thorne, Eds. (Australian Institute of Aboriginal Studies, Canberra, 1976), p. 55.
4. For Australian cultural chronology, see D. J. Mulvaney, *The Prehistory of Australia* (Penguin, Middlesex, England, ed. 2, 1975).

5. P. Rich, personal communication.
6. A. E. Newsome, *Aust. J. Zool.* **13**, 735 (1965).
7. G. B. Sharman, H. J. Frith, J. H. Calaby, *CSIRO Wildl. Res.* **9**, 20 (1964).
8. D. R. Horton and J. Samuel, *Aust. J. Zool.*, in press.
9. P. Crabb, personal communication.
10. See also D. R. Horton, *Artefact* **1** (No. 3), 129 (1976).
11. D. R. Horton, *Aust. Inst. Aboriginal Stud. Newsl.* **9**, 27 (1978).
12. For the method see R. Gillespie and R. B. Temple, *Radiocarbon* **15**, 566 (1973).
13. R. M. Jones, *Archaeol. Phys. Anthropol. Oceania* **3**, 186 (1968).
14. The work at Lancefield has been supported by grants from the University of Sydney, the Australian Institute of Aboriginal Studies, the National Museum of Victoria, and the Department of Mines. This report was edited by R.V.S.W.

6 December 1977; revised 6 March 1978

Atomic Hydrogen on Mars: Measurements at Solar Minimum

Abstract. *The Copernicus Orbiting Astronomical Observatory was used to obtain measurements of Mars Lyman-α (1215.671-angstrom) emission at the solar minimum, which has resulted in the first information on atomic hydrogen concentrations in the upper atmosphere of Mars at the solar minimum. The Copernicus measurements, coupled with the Viking in situ measurements of the temperature (170° ± 30°K) of the upper atmosphere of Mars, indicate that the atomic hydrogen number density at the exobase of Mars (250 kilometers) is about 60 times greater than that deduced from Mariner 6 and 7 Lyman-α measurements obtained during a period of high solar activity. The Copernicus results are consistent with Hunten's hypothesis of the diffusion-limited escape of atomic hydrogen from Mars.*

A bright Lyman-α (1215.671-Å) dayglow, arising from the resonant scattering of solar Lyman-α photons by atomic hydrogen (H), appears to be a regular feature of planetary exospheres. Rockets, satellites, and planetary probes have measured Lyman-α emission emanating from the terrestrial exosphere and the geocorona, as well as from the hydrogen coronae of Mars (measured by Mariner 6, 7, and 9), Venus (Mariner 5 and 10), Mercury (Mariner 10), and Jupiter (Pioneer 10 and 11). A comprehensive review of the hydrogen coronae of the terrestrial planets has recently appeared (*1*).

The first measurements of Mars Lyman-α emission were obtained in July and August 1969 with the ultraviolet spectrometers aboard the Mariner 6 and 7 flybys during a period of high solar activity (*2, 3*). A similar ultraviolet spectrometer aboard the Mariner 9 orbiter obtained Mars Lyman-α measurements between November 1971 and February 1972, also during a period of high solar activity (*4, 5*). Interpretation of the Mariner Mars Lyman-α emission measurements with a spherical radiative transfer model has led to our present understanding of both the H distribution in the martian corona and the escape of H from Mars (*3, 5*). Knowledge of the exospheric distribution and escape of H (a photolytic product of H_2O), and of how the distribution and escape of H vary with the level of solar activity, is important in assessing the evolution of H_2O over the history of Mars (*6*).

We report here on the first measurements of Mars Lyman-α emission obtained during a period of low solar activity. In addition, the measurements obtained with the Copernicus Orbiting Astronomical Observatory (OAO-3) are the first measurements of Mars Lyman-α emission obtained from the vicinity of Earth. We will discuss the characteristics of the Mars hydrogen corona, deduced from our analysis of these measurements, coupled with the recent Viking in situ measurements of the upper atmospheric temperature of Mars, and will compare them with the Mariner 6 and 7 Lyman-α measurements.

Copernicus was launched into a 750-km circular orbit in August 1972. The Princeton Experiment Package (PEP) on Copernicus consists of a 32-inch (80-cm) Cassegrain telescope with a Paschen-Runge spectrometer, which utilizes a concave grating to focus the spectrum on a 1-m Rowland circle. Two movable carriages, each equipped with two photomultiplier tubes, scan the spectrum. For the Mars measurements, we used the U1 photomultiplier tube with a band-pass width of 0.04 Å, centered at the H Lyman-α line at 1215.671 Å. The spectrometer entrance slit was placed on the centroid of light of the visible disk of Mars. The Copernicus entrance slit is 39 arc sec long by 0.3 arc sec wide. In September 1975, Mars was about 9 arc sec in diameter. The spectrometer scan is placed at the blue end of the line and is moved every 14 seconds to a new position in 0.02-Å intervals across the line. The complete scan from about 1215.5 to 1215.8 Å takes about 8 minutes.

The Copernicus measurement procedure consisted of one orbit ON Mars, followed by one orbit OFF Mars (about 60 arc sec off the Mars disk). The ON-OFF measurement procedure continued for about 11 orbits on 6 to 8 September 1975, yielding a total of about 49 scans of the geocorona and Mars Lyman-α emission spectra.

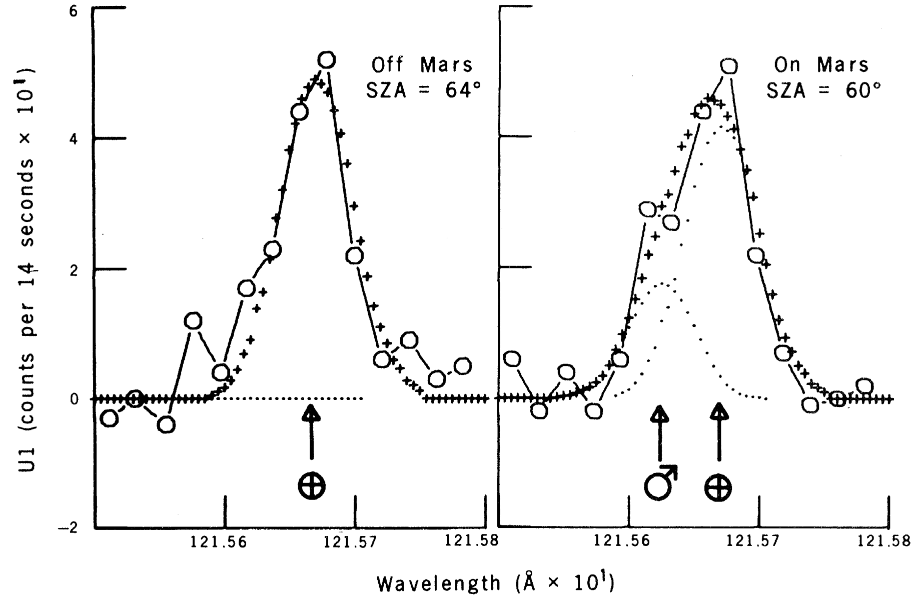

Fig. 1 (left). Copernicus spectrum of geocoronal Lyman-α radiation (OFF Mars) for SZA = 64°. The vertical arrow indicates the Lyman-α line center. The circles are the Copernicus measurements, and the pluses are derived from a least-squares fit (see text). Fig. 2 (right). Copernicus spectrum of geocoronal and Mars Lyman-α radiation (ON Mars) for SZA = 60°. The vertical arrows indicate the Mars and geocoronal Lyman-α line centers. The circles are the Copernicus measurements; the pluses are derived from a least-squares fit and are the sum of the two individual profiles of the geocoronal and Mars Lyman-α spectrum indicated by the small dots.

0036-8075/78/0602-1048$00.50/0