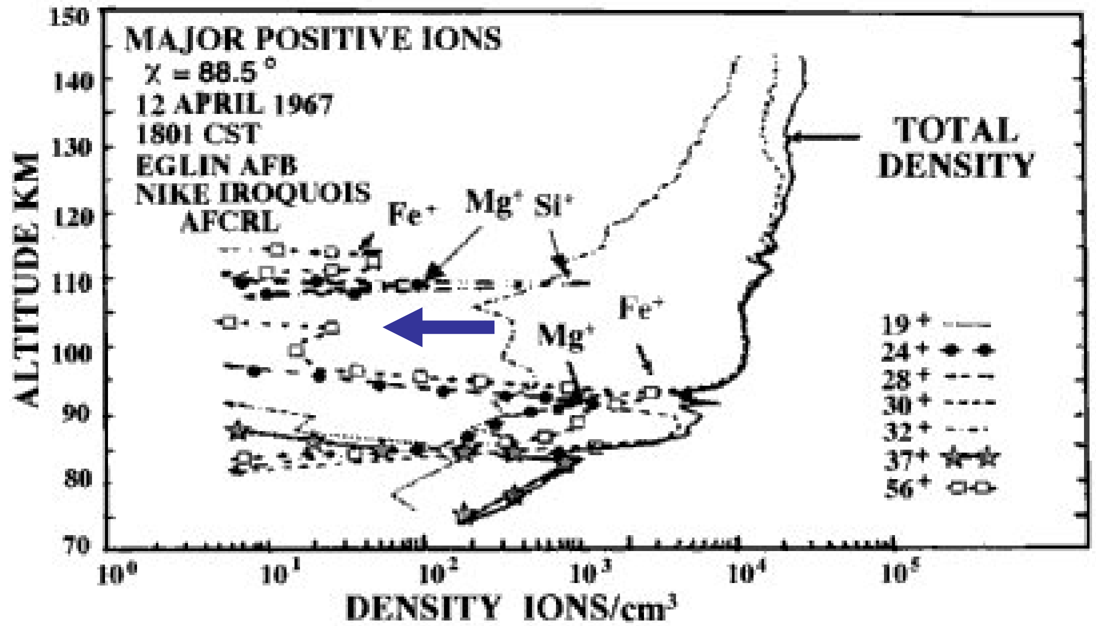
Plasma layers in the terrestrial, martian and venusian ionospheres: Their origins and physical characteristics

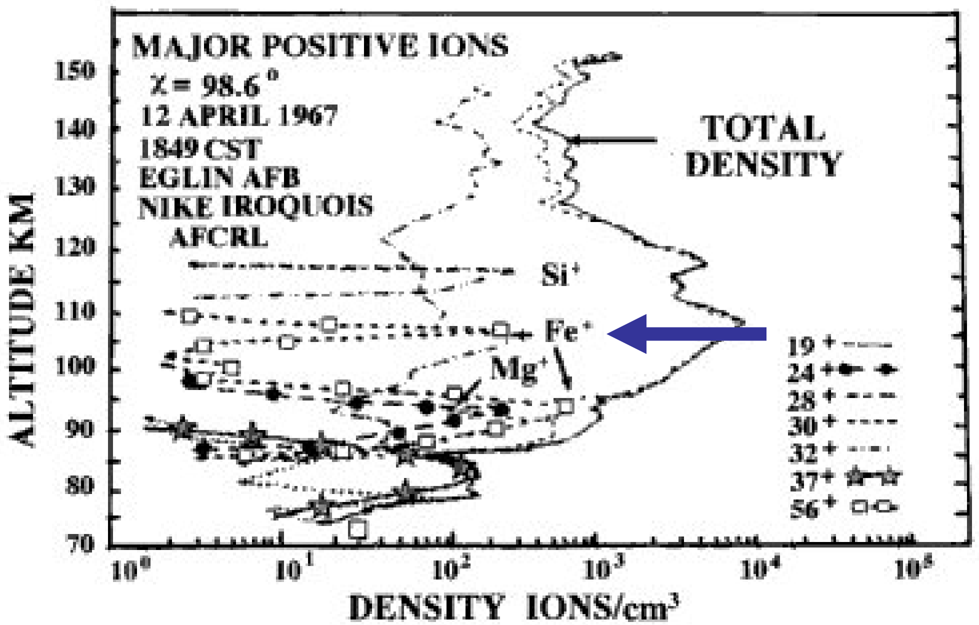
Martin Patzold (University of Cologne)
and Paul Withers (Boston University)

Europlanet N3 Fourth strategic workshop on meteor studies

2008.09.27, Cologne, Germany



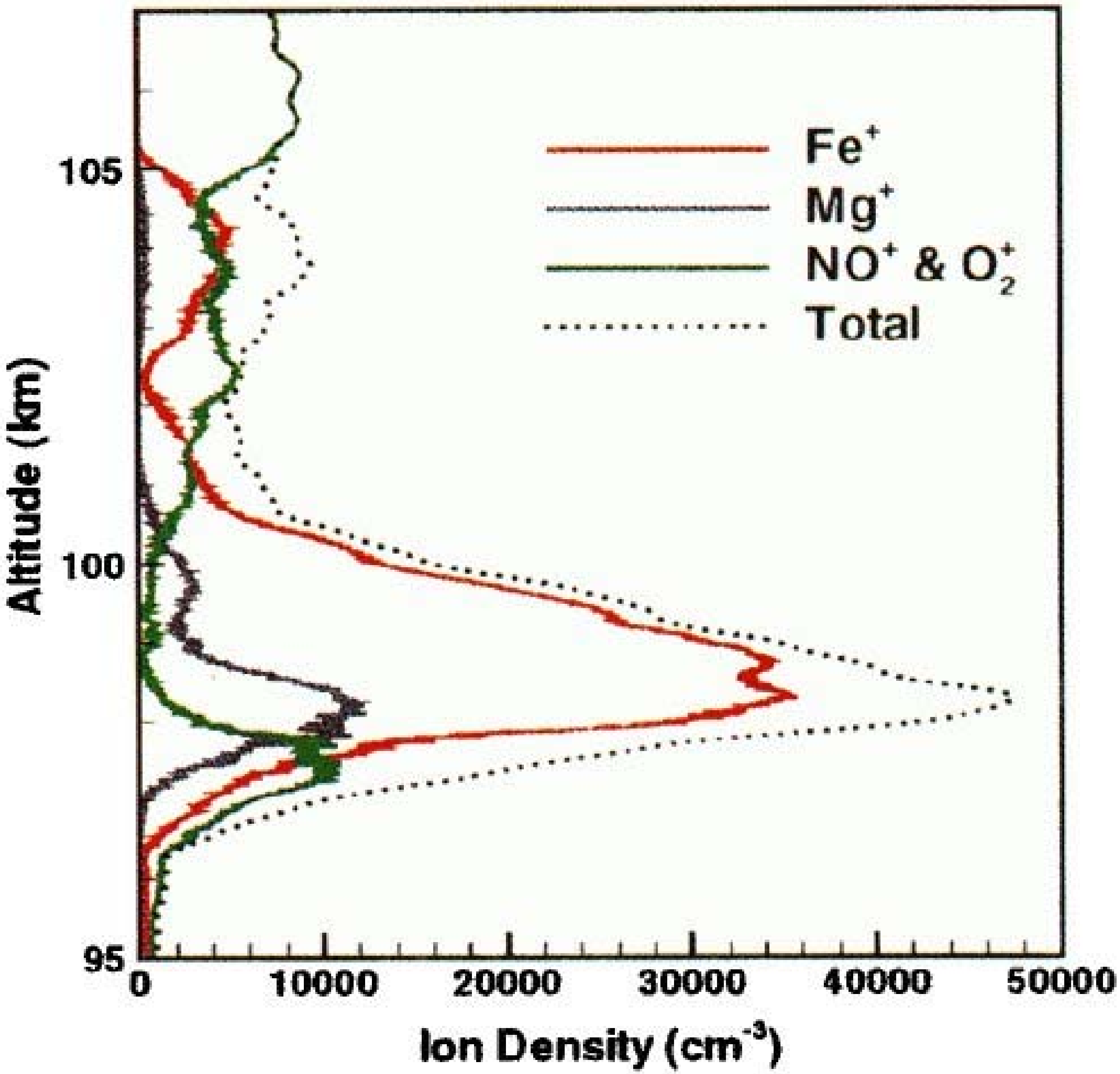
Before sunset



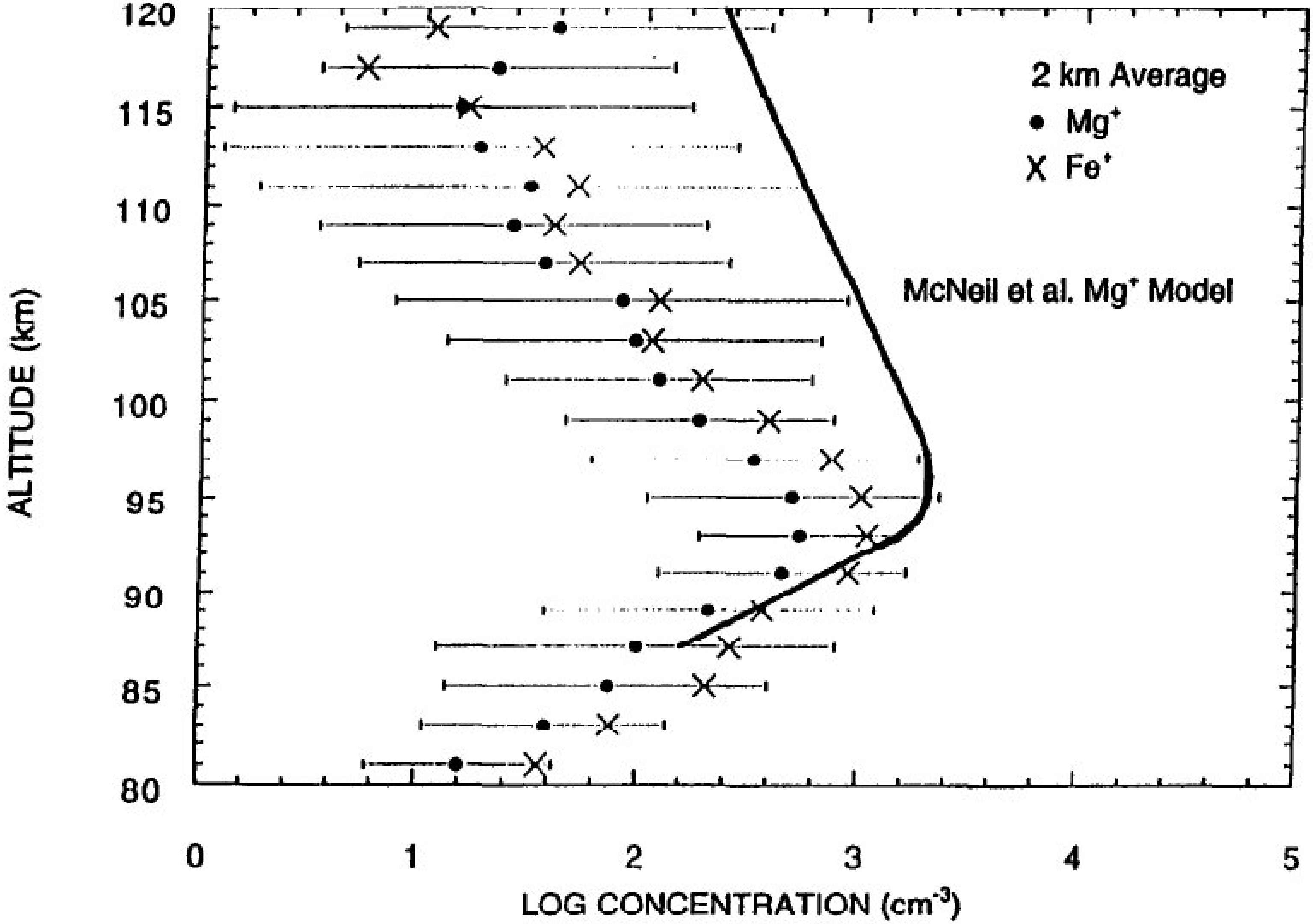
50 minutes later, after sunset

Meteoric layers are longer-lived than molecular ions, but they are highly variable

From Grebowsky and Aikin (2002)



Rocket flight, Arecibo, 2145 local time (after sunset). From Earle et al. (2000).



Average of all available rocket data (41 flights). Average looks much smoother than an individual observation, no narrow layering.
From Grebowsky et al. (1998).

Discovery of terrestrial meteoric layers

- Layer of metallic (Mg^+, Fe^+) ions detected around 100 km by first ion mass spectrometers launched on rockets (~1960).
- It was quickly(?) accepted that these ions derived from meteoroids, which ablate at similar altitudes.
- Complex processes control metallic layers
  - (1) metallic species are deposited as ions and neutrals;
  - (2) neutrals are ionized;
  - (3) ions are transported horizontally and vertically;
  - (4) ions are neutralized

(1) Deposition of metallic species

- Meteoroids ablate during entry, delivering metallic atoms (not molecules) into an atmosphere that usually doesn’t contain metals
- Conservation of energy, momentum and mass
- The deposition rate of metallic species is low at very high and very low altitudes, with a maximum at a favourable altitude – a layer
- Altitude and width of deposition profile are affected by: meteoroid size and speed, atmospheric density and scale height
- Fraction of ablated metal atoms that are ionized during ablation is affected by entry speed.

(2) Ionization of neutral metal atoms

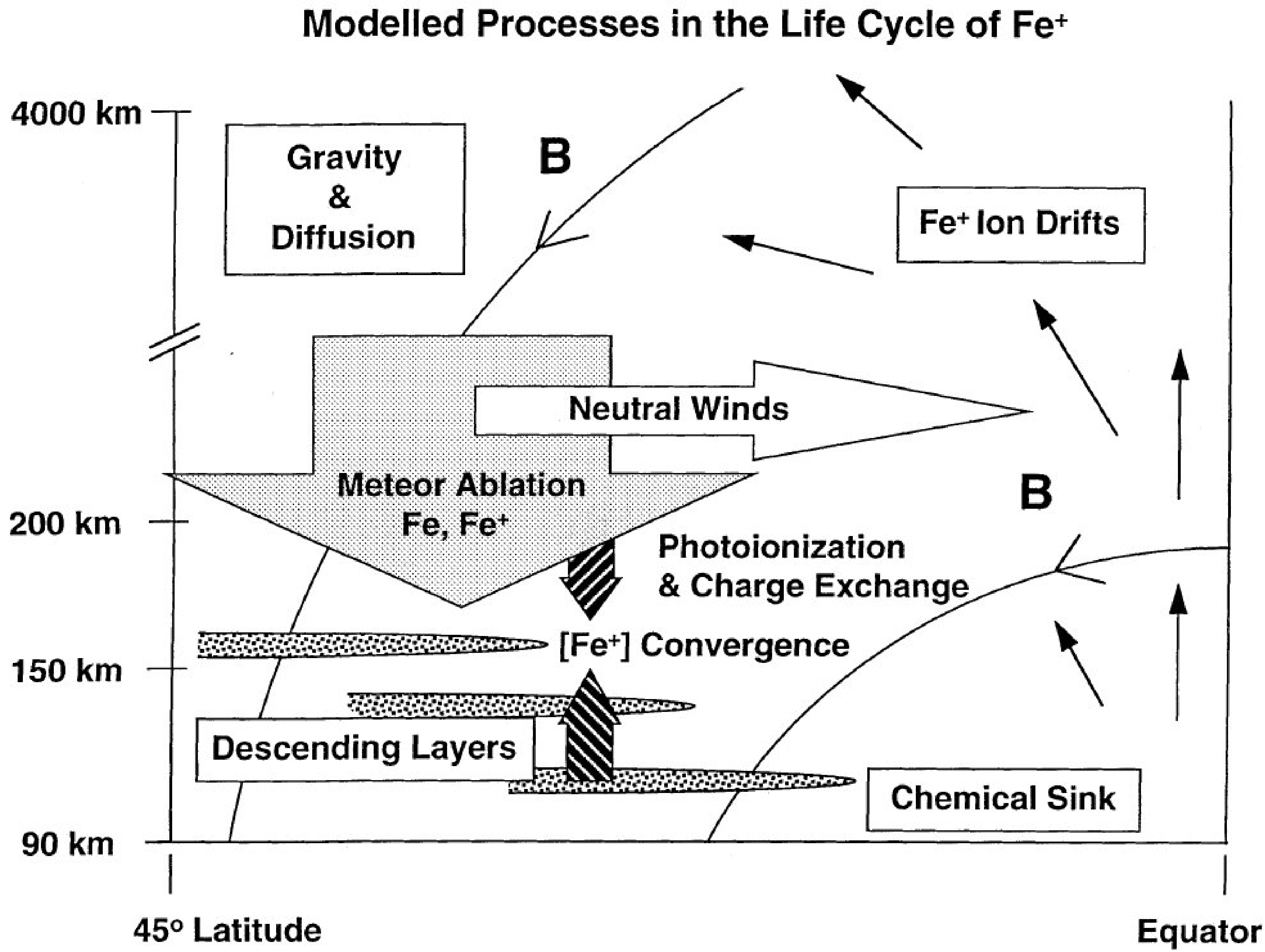
- Metal atoms can be photoionized by solar radiation
  - Depends on how opaque overlying atmosphere is at relevant range of wavelengths.
- Metal atoms can be ionized by charge exchange with more common ions
  - Depends on the typical ionosphere of the planet
  - e.g. $M + O_2^+ \rightarrow M^+ + O_2$
- Also, a fraction of ablated metal atoms are instantly ionized during ablation
  - Depends on entry speed
- Atomic, not molecular, ions are most abundant

(3) Transport of ions

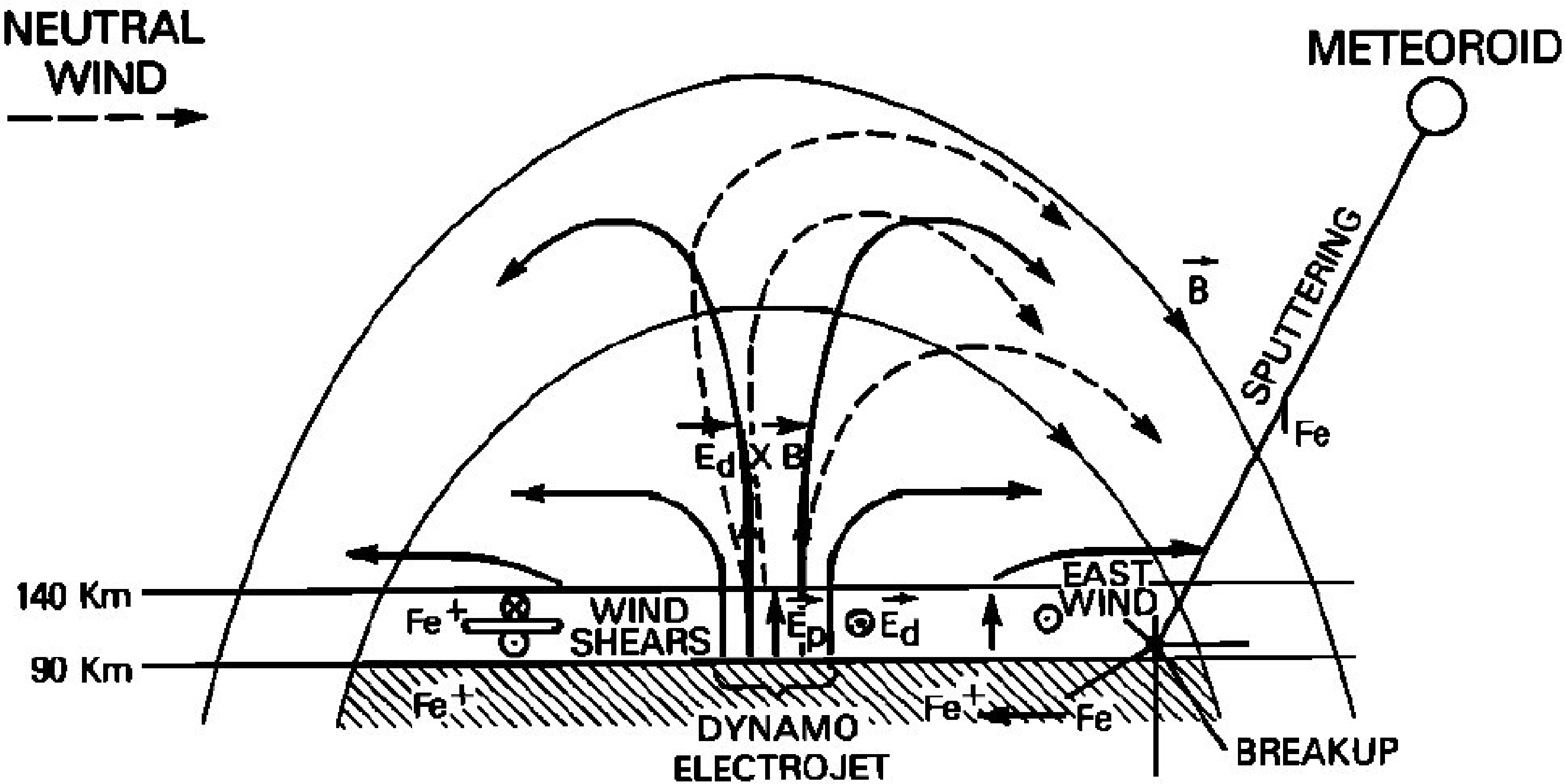
- Complicated on Earth, unknown on Venus and Mars
- Strong terrestrial magnetic fields and atmospheric waves can combine to produce sharp layers of metal ions
- Electric fields move plasma meridionally and in local time, especially important in tropics
- Electromagnetic forces can also move plasma upwards to high altitudes
- Potential for different behaviour on non-magnetized Venus and patchily-magnetized Mars.
- Diffusion downwards is the ultimate sink

(4) Neutralization of ions

- $M^+ + e \rightarrow M$ is very slow
- $MO^+ + e \rightarrow M + O$ is faster
- So M^+ has a long lifetime, but MO^+ does not.
- Molecular metal ions are produced from atomic metal ions by two-body reactions, e.g. $M^+ + O_3 \rightarrow MO^+ + O_2$ or three-body reactions, e.g. $M^+ + O_2 + X \rightarrow MO_2^+ + X$
- Since conversion rate depends on neutral density, conversion of long-lived atomic ions into short-lived molecular ions is fast at low altitudes.
- Rate of downwards transport of metallic ions is important for controlling their lifetime



Schematic of physical processes that affect meteoric layers.
From Carter and Forbes (1999).



DAYSIDE METALLIC ION SOURCES

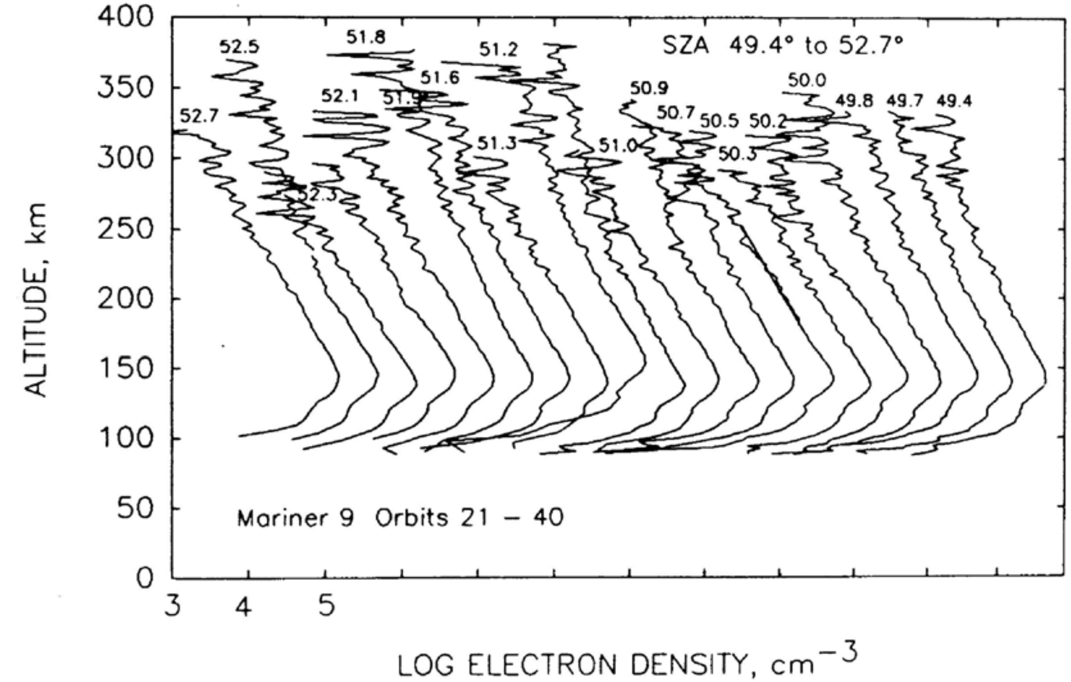
Equatorial fountain effect. Vertical electric fields near the equator can accelerate plasma upwards from source region to 200-300 km, where lifetimes are very long. From Grebowsky and Reese (1989).

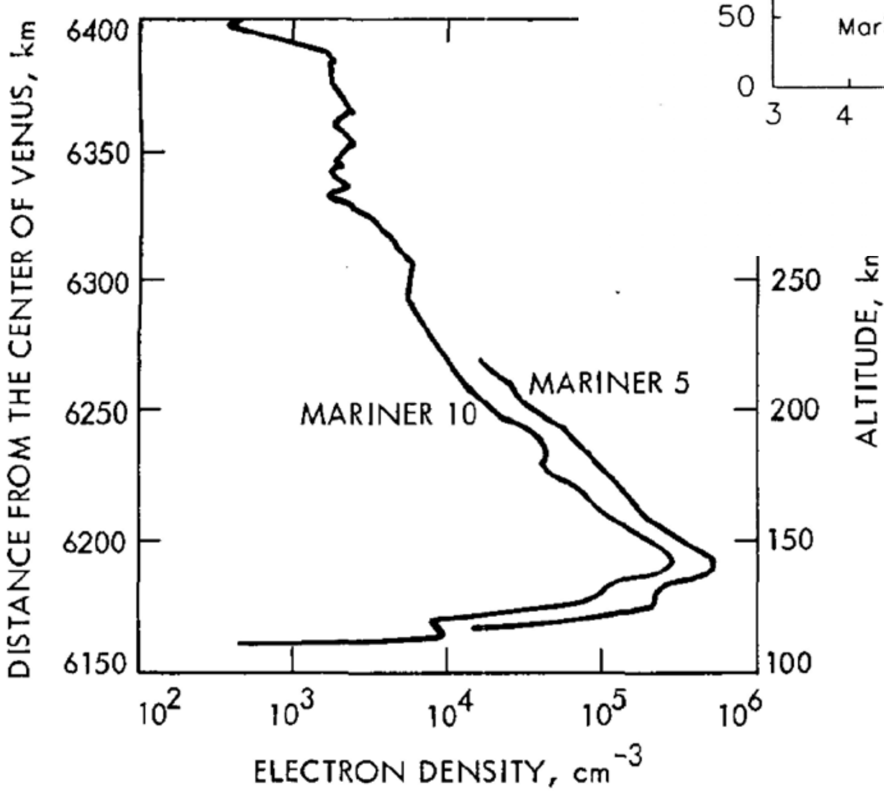
“The continuous global influx of the sporadic background of meteoroids might be expected to lead, through ablation, to a single contiguous global layer of neutral metal atoms. A simple picture . . . is that there would be a single global-wide layer of meteoric ions in the ablation region” (Grebowsky & Aikin 2002). Indeed, a metallic ion layer is consistently observed between 90 and 100 km — although “its most distinctive property . . . is its variability” and ±1 standard deviation about the mean concentration spans one order of magnitude (Grebowsky & Aikin 2002). Peak altitude decreases from mid to high latitudes and increases from dayside to nightside. Additional narrow layers are sometimes observed above 100 km (~110–120 km) at mid, but not high, latitudes. Double layers below 100 km have been observed at high latitudes (Grebowsky & Aikin 2002). Satellites have detected metallic ions at altitudes up to 500 km, far above the ablation region. High altitude ions have been detected at all latitudes, but extend to higher altitudes at equatorial latitudes than at other latitudes (Grebowsky & Aikin 2002). At low latitudes, metallic ions are most common at afternoon-dusk local solar times (LSTs). The simple picture of a single global-wide layer of meteoric ions in the ablation region is not supported by observations.

Summary for Earth

- Lots of data
- Properties of layers are spatially and temporally variable
- Models reproduce typical characteristics, not individual observations
- Many important processes depend on strong magnetic field

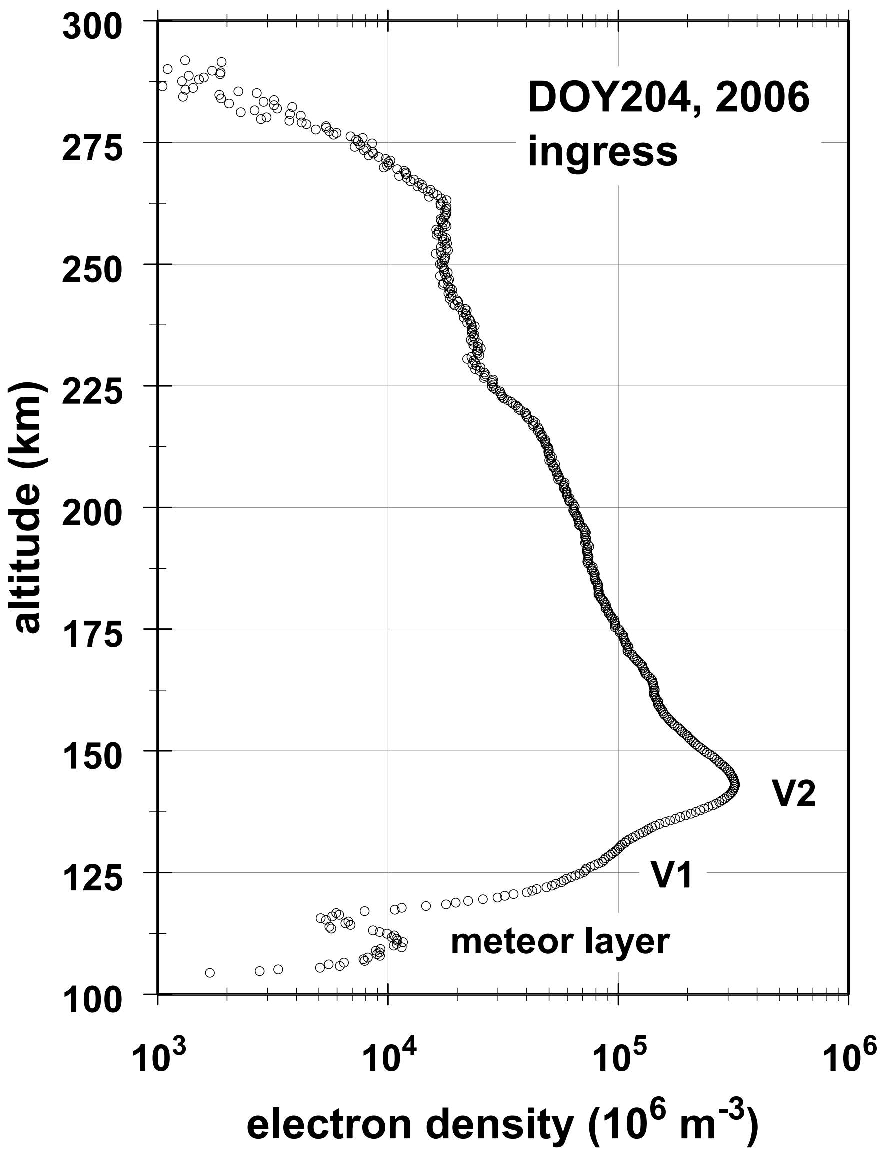
(right) Likely meteoric layers observed at Mars in 1971. From Kliore (1992).



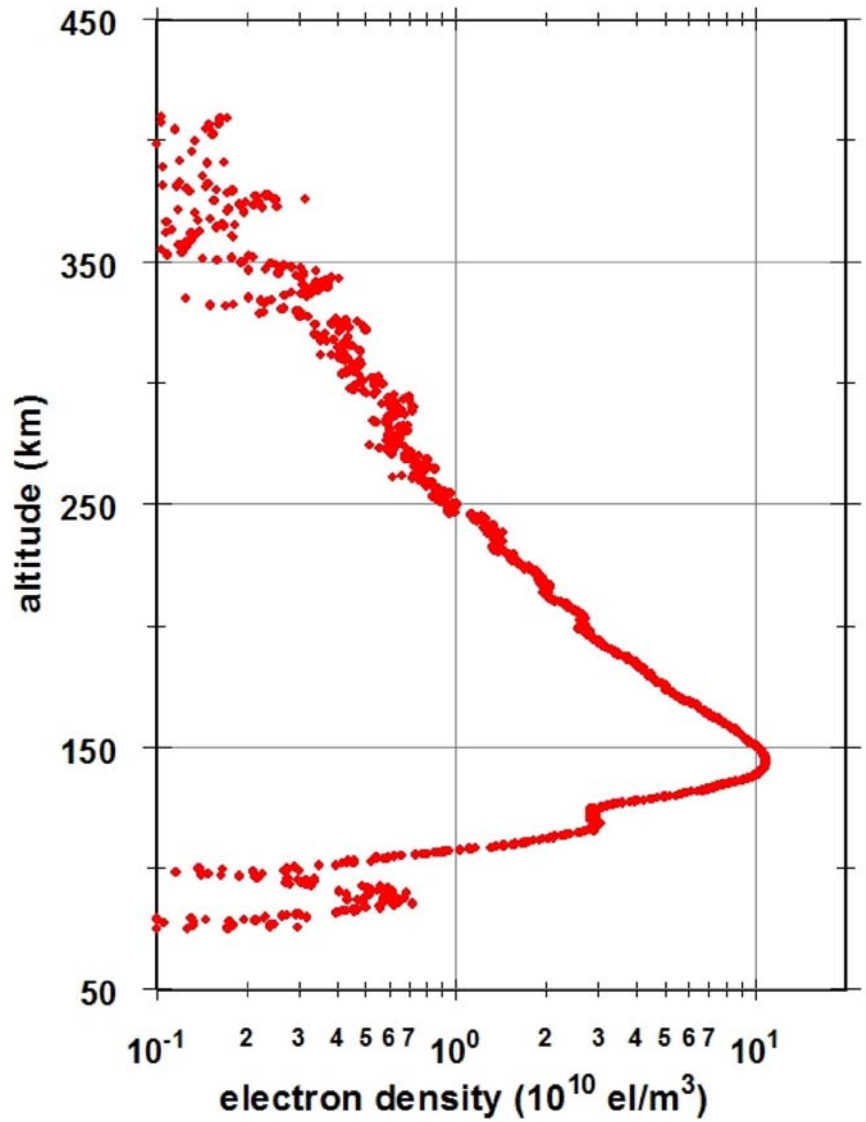


(left) Likely meteoric layer observed at Venus in 1974. From Fjeldbo et al. (1975).

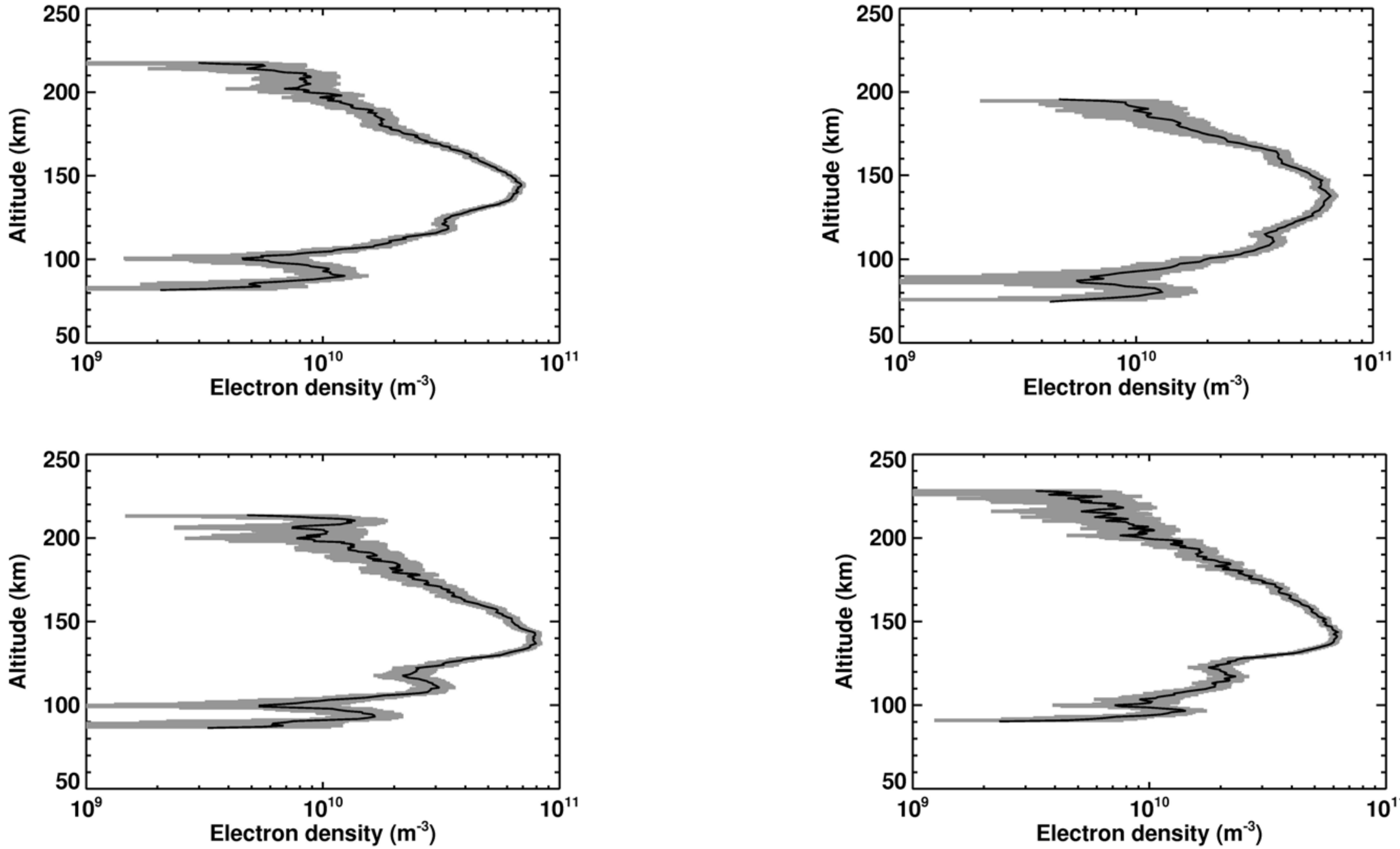
Old observations show apparent meteoric layers, but these were not identified at the time.



Meteoric layer from Venus Express (VEX)



Meteoric layer from Mars Express (MEX)



Four MGS profiles with meteoric layers

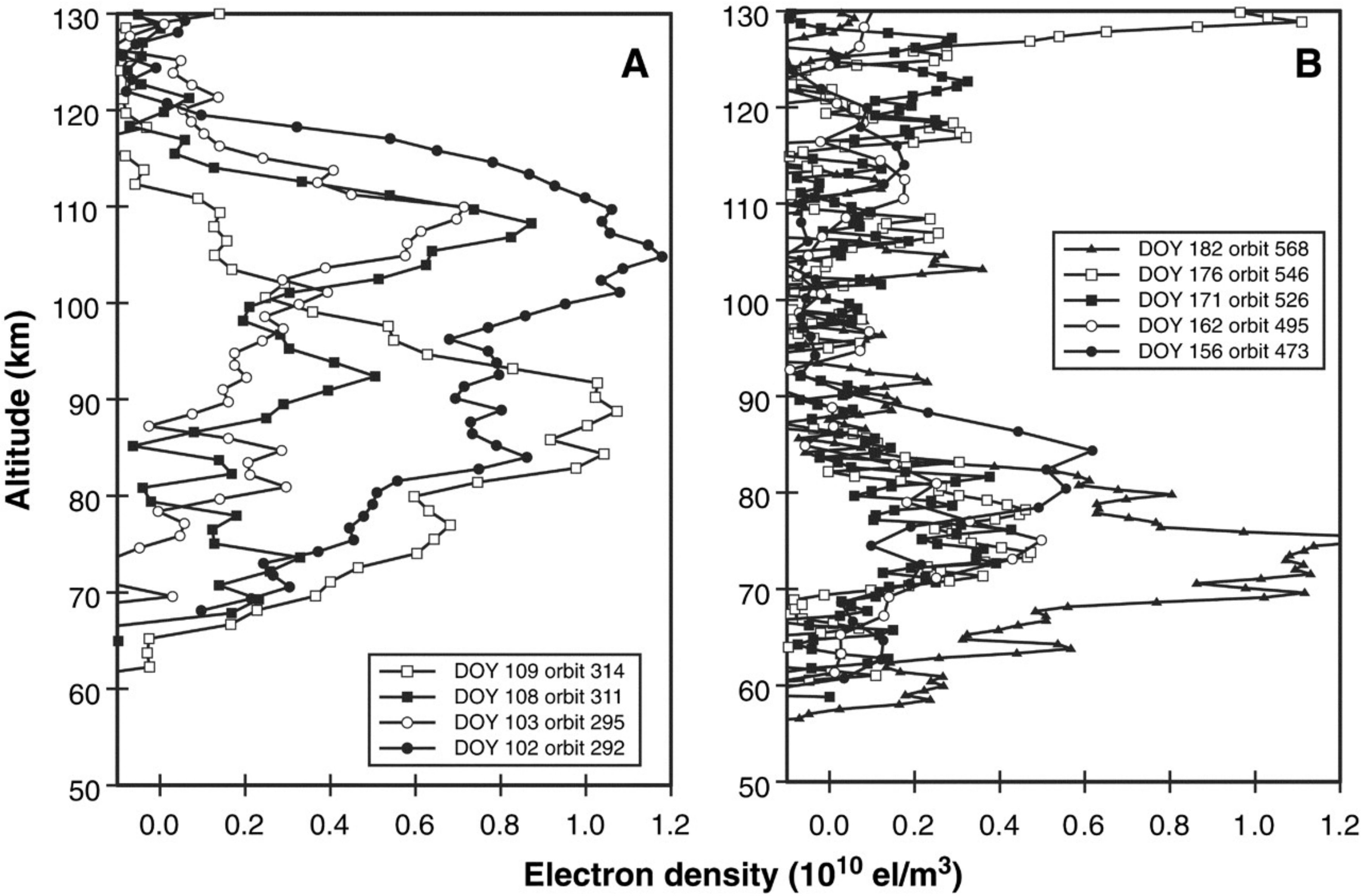
Martian meteoric layers (MGS)

- Seen in 71 of 5600 profiles
- Altitude 91.7 +/- 4.8 km
- Width 10.3 +/- 5.2 km
- Electron density (1.33 +/- 0.25) x 10^{10} m^{-3}
- All three of these are positively correlated (r~0.4)
- None of these are correlated with solar zenith angle, solar flux, etc, unlike other ionospheric layers

Implications

- Width of meteoric layers varies by factor of four, much more variable than any scale height. So what controls width?
- Altitude varies by 2 scale heights, electron density varies by factor of 2, width varies by a factor of four. What causes such large variability?

MEX layers



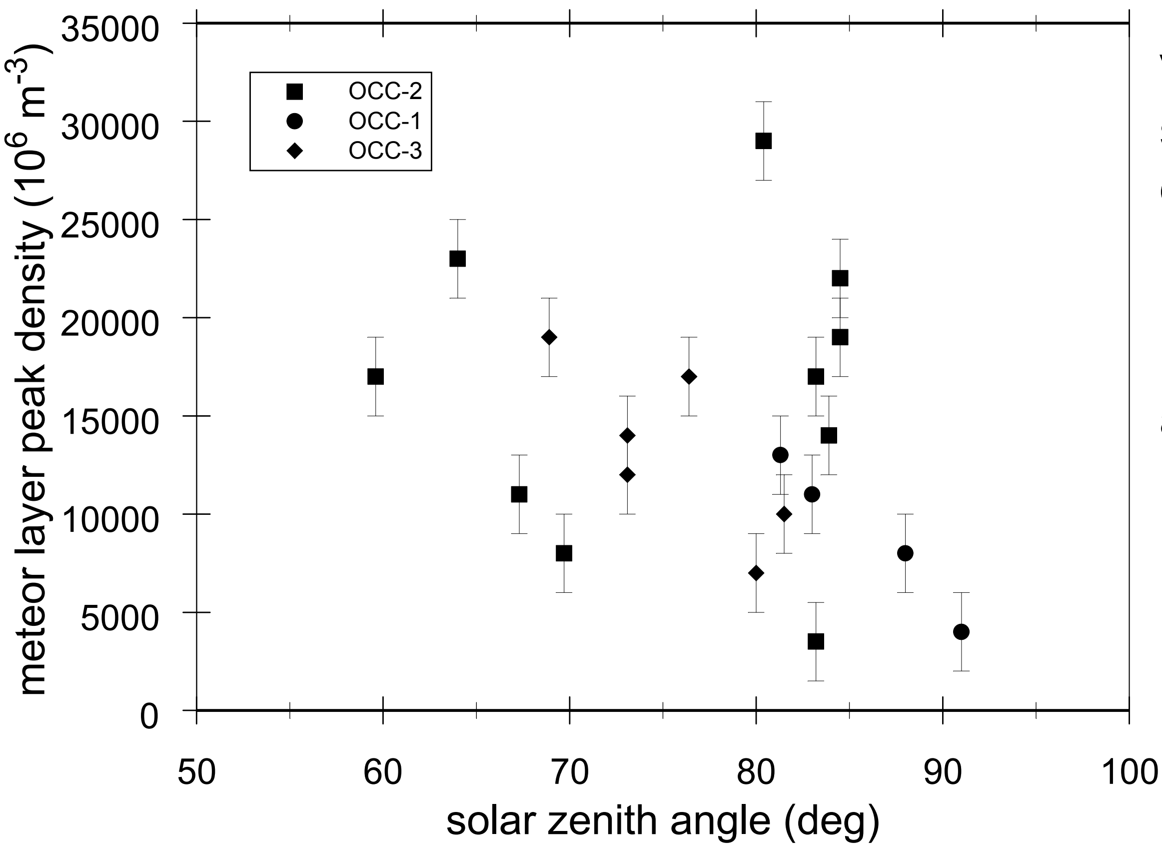
A
B
Altitude (km)
Electron density (10^{10} el/m^3)
130
120
110
100
90
80
70
60
50
0.0
0.2
0.4
0.6
0.8
1.0
1.2
DOY 109 orbit 314
DOY 108 orbit 311
DOY 103 orbit 295
DOY 102 orbit 292
DOY 182 orbit 568
DOY 176 orbit 546
DOY 171 orbit 526
DOY 162 orbit 495
DOY 156 orbit 473

MEX layers

- Seen in 75 of 465 profiles
- Altitude, width, electron density similar to MGS
- Altitude and width are positively correlated
- Altitude increases as solar zenith angle increases (not seen in MGS)

VEX layers

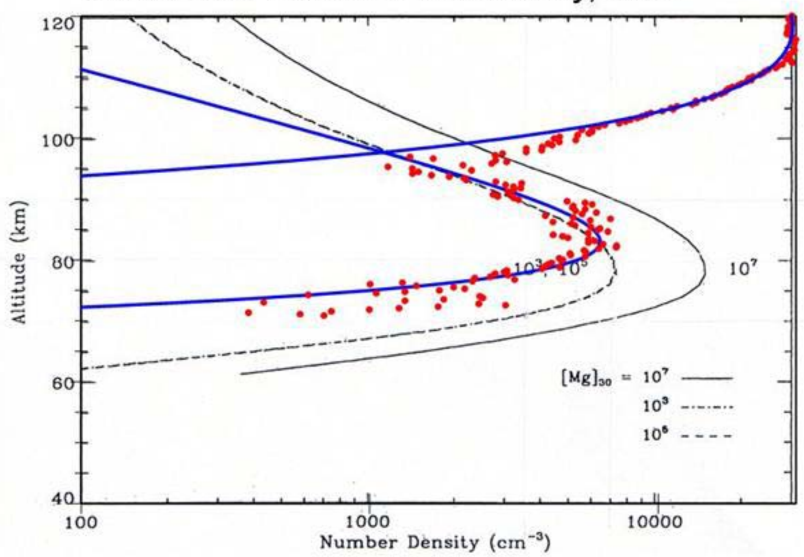
- Altitude ~110 km, width ~10 km, electron density ~10^{10} m^{-3},



VEX studies are at an early stage. 18 of about 60 dayside profiles contain meteoric layers.

No layers seen at solar zenith angles < 55 deg?

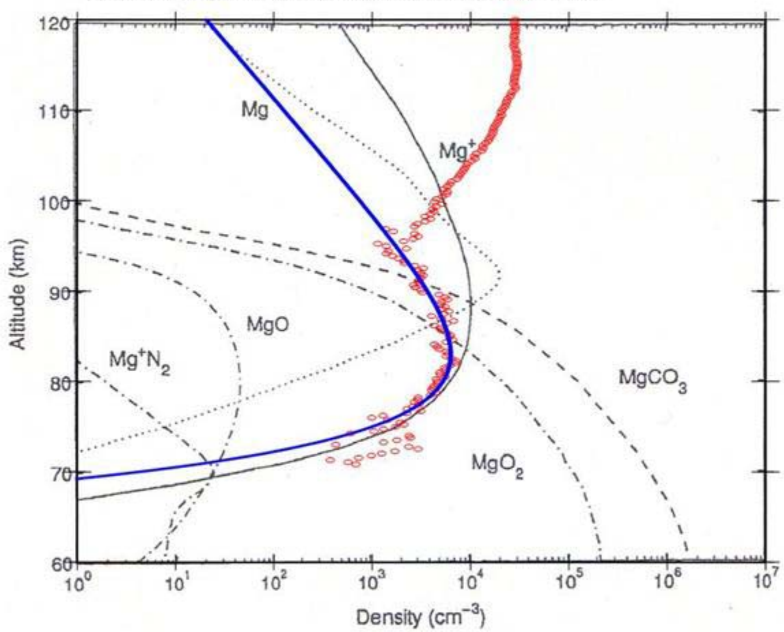
Model from Pesnell & Grebowsky, 2003



Models for Mars

- Only two published papers predict N(z) for metallic ions
- Each uses fixed solar zenith angle, meteoroid flux, etc
- No predictions of variability in anything

Model from Molina-Cuberos et al., 2003

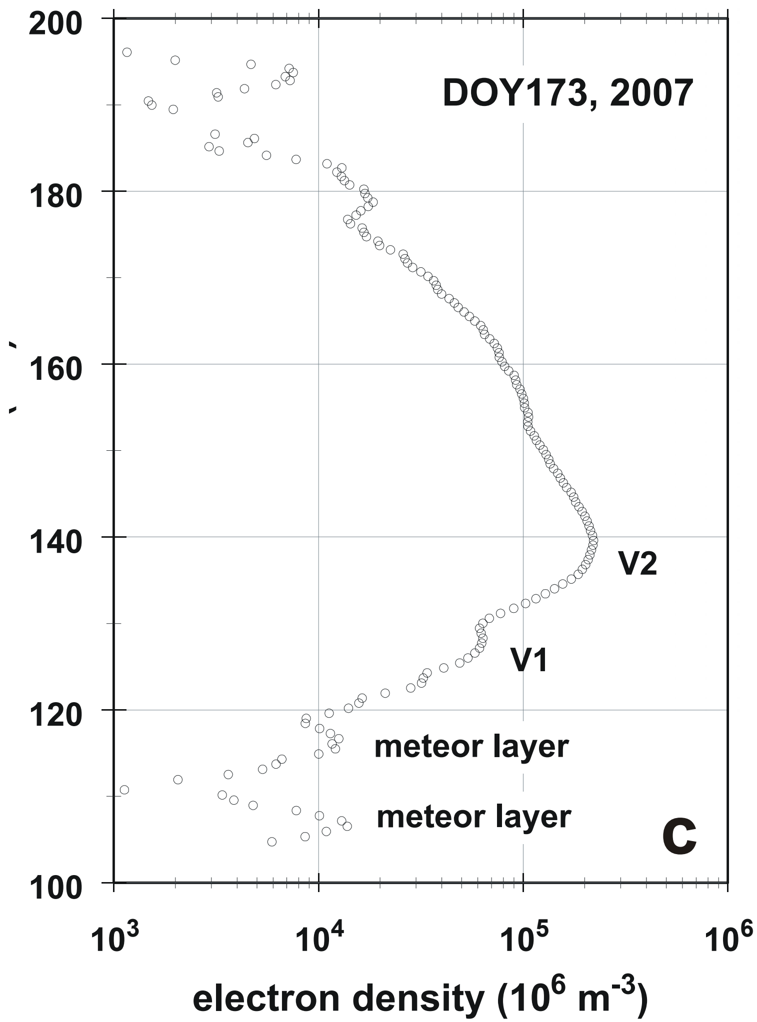


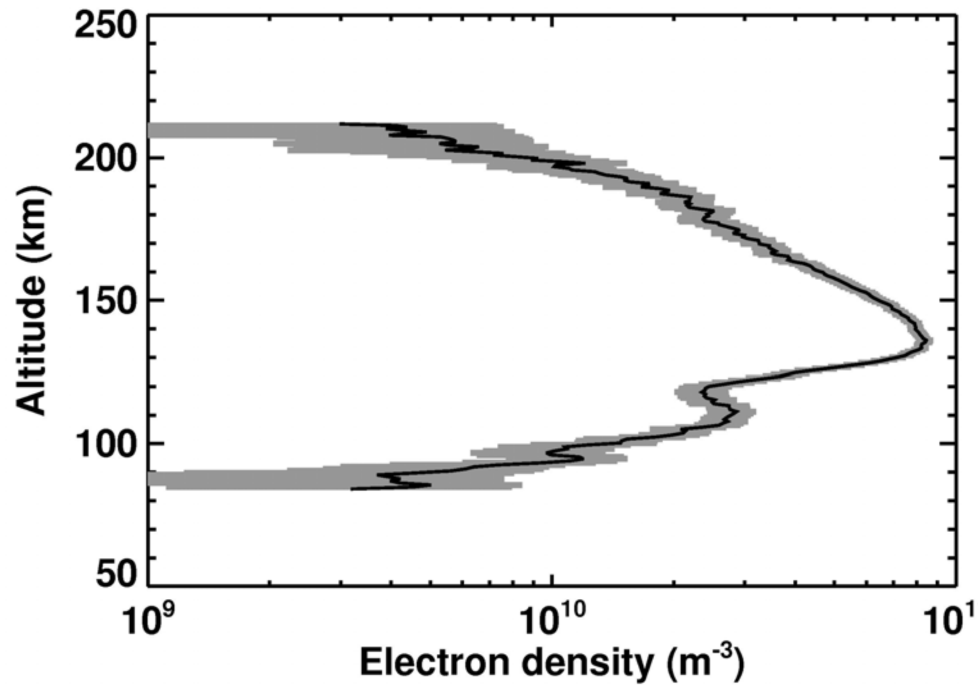
- Predicted altitude ~80-90 km (OK)
- Predicted full-width-at-half-max ~20 km (too large)
- Predicted densities ~10^{10} m^{-3} (OK)

Models for Venus

- Even fewer published predictions. N(z) for Venus shown in Grebowsky et al. (2002), but no details given.
- Predicted altitude ~110 km (OK)
- Predicted width ~10 km (OK)
- Predicted densities ~10^7 m^{-3} (not 10^{10} m^{-3})
- Further simulations are needed!

Multiple layers





Multiple meteoric layers have been observed by (left) VEX and right (MGS). Multiple layers are common on Earth. They are a major challenge for alternate theories for the origin of these layers.

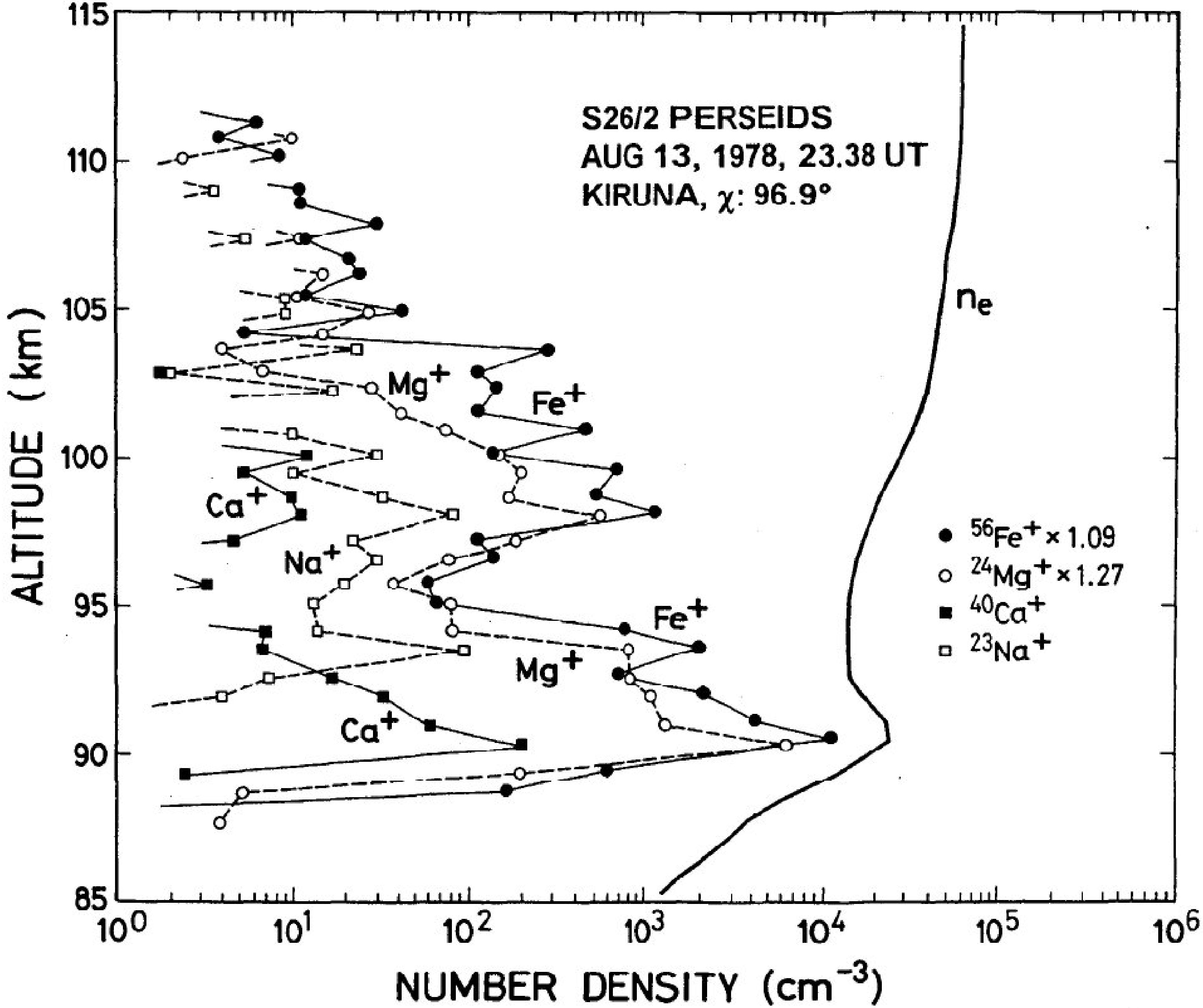
Challenges for models

- What is dominant ionization process?
  - Ablation, photoionization, charge exchange?
- What causes the large variations in physical characteristics?
- Why are layers not always seen?
- Which important terrestrial mechanisms are (and are not) important on Venus and Mars?

Conclusions

- Layers of meteoric plasma have been studied on Earth for 50 years and have just been discovered on Venus and Mars.
- Altitudes, widths, electron densities of meteoric layers vary greatly on all three planets.
- Simulations of meteoric layers on Venus and Mars are needed.

Backup



From Kopp (1997).