Note – Professor Withers has not received NSF funding in the past five years.

1 – Introduction to planetary ionospheres

"The ionosphere is considered to be that region of an atmosphere where significant numbers of free thermal electrons and ions are present. All bodies in our solar system that have a surrounding neutral-gas envelope, either due to gravitational attraction (e.g. planets) or some other process such as sublimation (e.g. comets), have an ionosphere. Currently, ionospheres have been observed around all but two of the planets, some moons, and comets. The free electrons and ions are produced via ionization of the neutral particles both by extreme ultraviolet radiation from the Sun and by collisions with energetic particles that penetrate the atmosphere. Once formed, the charged particles are affected by a myriad of processes, including chemical reactions, diffusion, wave disturbances, plasma instabilities, and transport due to electric and magnetic fields" (Schunk and Nagy, 2009).

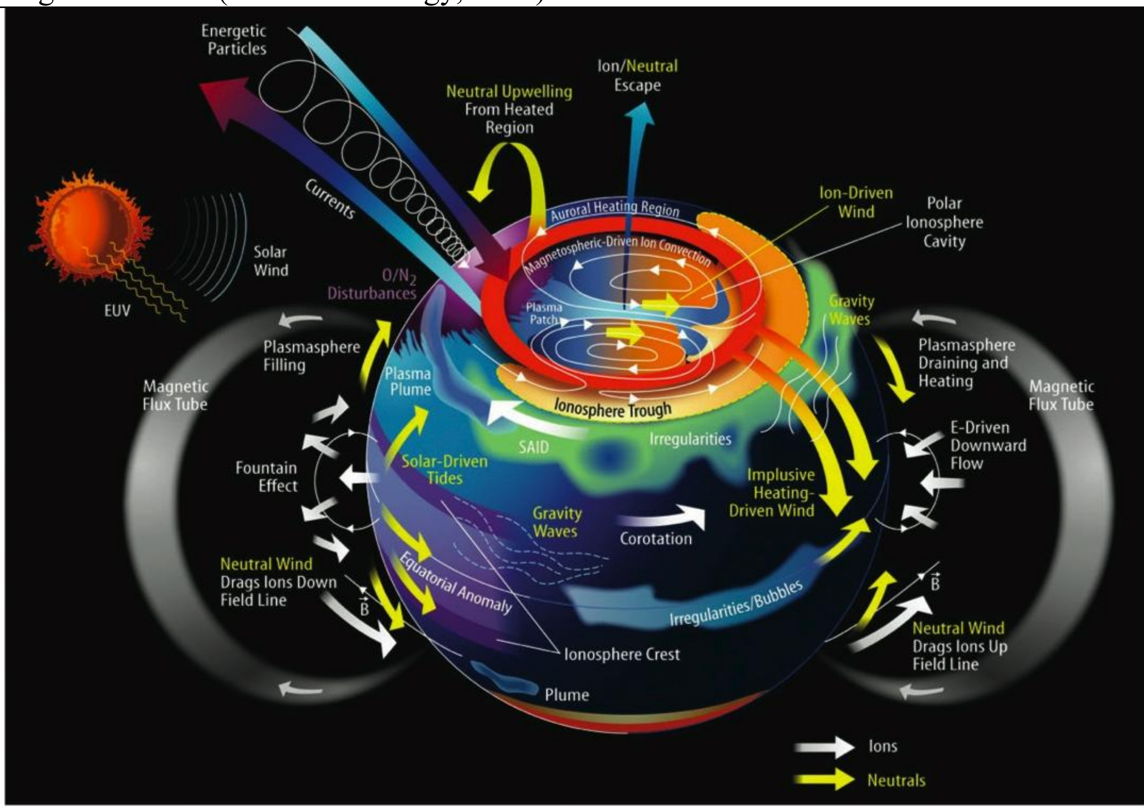

Fig. 1. Schematic illustration of prominent features in Earth's ionosphere and the physical processes that maintain them. The ionosphere affects the neutral atmosphere and the planet's interaction with the space environment. Image from NASA.

Ionospheres are important in planetary science (Fig. 1) as part of the boundary between a planetary body and the surrounding space environment (Kelley, 1989; Rees, 1989; Schunk and Nagy, 2009). Some of the most energetic components of the Sun's output, both photons and particles, are absorbed at ionospheric altitudes. As a result of the disruption this energy deposition causes to bonds within molecules, ionospheric chemistry can differ significantly from the chemistry of the bulk neutral atmosphere. In addition, ionospheric temperatures are both high and variable. As the charged constituent of the atmosphere, an ionosphere is the only atmospheric region affected by electric and magnetic fields, including those imposed by the external space environment. If atmospheric loss to space is significant at a planetary body, with all the associated implications for climate and surface conditions, then its ionosphere will play a major role in this. Ionospheric ions are close enough to the exobase to be accessible to many escape process and, since they are charged, they often play a much more significant role in escape than their low number density relative to surrounding neutral species would suggest. Ionospheres also play a role in atmospheric science: an ionosphere interacts strongly with the neutral atmosphere that surrounds it. Its chemistry is rooted in the chemistry of the neutral atmosphere and its dynamics are driven by the circulation of the neutral atmosphere. Yet the coupling acts both ways: ionospheric processes can deliver momentum and energy to, or extract them from, the neutral atmosphere.

Ionospheres are relevant to some of the major questions in planetary science today:
- Did Mars ever possess surface oceans and an environment hospitable to life?
- How does the space environment interact with planets?
- What is the origin and history of Titan's volatiles?
- How do internal magnetic fields affect the evolution of planets?
- How do variations in the Sun affect Earth?

2 – Introduction to the Venus ionosphere

The Venus thermosphere (~100-200 km) lies just below the exobase, the effective boundary between the planet and outer space. It is strongly affected by the dynamics and thermal structure of the underlying atmospheres, and also by its interactions with the impinging solar wind. Embedded within the thermosphere is the ionosphere, a weakly ionized and cold plasma (see articles in Hunten et al., 1983, and Bougher et al., 1997, for further ionospheric overviews and in-depth discussions of the primary literature). At altitudes below ~180 km, the dayside ionosphere is dominated by O_2^+ ions (Figs 3 and 8). These originate in the photoionization of neutral carbon dioxide, the most abundant constituent in the bulk atmosphere (CO_2 + photon -> CO_2^+ + e, CO_2^+ + O -> O_2^+ + CO, O_2^+ + e -> O + O). At higher altitudes, O^+ ions are dominant (Fig 3), reflecting the transition in the neutral composition from CO_2-dominated below the homopause (~140 km) to lighter O being most abundant by about 180 km. A range of other ion species are also present, including CO_2^+, CO^+, N_2^+, and NO^+. These ions are produced by photoionization of neutral species by solar extreme ultraviolet (EUV, 10-100 nm) and soft X-ray (1-10 nm) photons, electron impact ionization by photoelectrons (particularly important at low altitudes where energetic soft X-rays dominate the photoionization), ionization by precipitating particles like suprathermal electrons, and subsequent ion-neutral chemical reactions (Fox and Kliore, 1997). This proposal addresses the dayside ionosphere, so we do not discuss the surprisingly dense and complex nightside ionosphere of Venus.

Venus and Mars both possess carbon dioxide atmospheres. Although that of Venus is many times denser than that of Mars and incomparably nastier at the planetary surface, conditions at the pressure levels where planetary ionospheres occur (i.e., ~1 nbar, optical depth of unity for ionizing solar radiation) are relatively similar. The temperatures here are approximately a few hundred Kelvin and the compositions are mostly CO_2 with a few percent of atomic oxygen. Why the temperatures are similar despite the factor of four difference in solar flux between Venus and Mars is an interesting study in thermospheric energy balance, (e.g. Bougher et al., 2002). The presence of atomic oxygen, a highly reactive species, is maintained by photodissociation of carbon dioxide. As a result, the ionospheres of the two planets are remarkably similar and comparisons between them are fruitful. An important research theme in planetary ionospheres is how are these two ionospheres similar, how are they different, and why. Factors likely to account for differences include the planet-Sun distance, the planet's rotation (which is a major driver for atmospheric dynamics as well as setting the duration of the photoionization-less nighttime), and O/CO_2 ratio. This ratio, which can control ionospheric composition, increases with solar flux and is hence appreciably greater at Venus than at Mars. It also varies with the solar cycle.

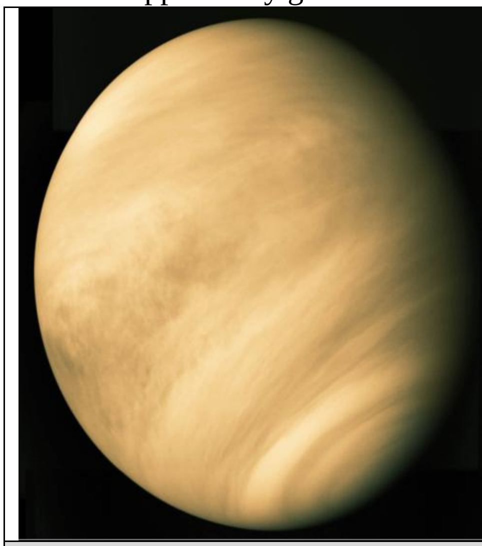

Fig. 2. Mariner 10 image of cloud-shrouded Venus. The Venus atmosphere is one of the most chemically interesting in the solar system. From www.solarviews.com.

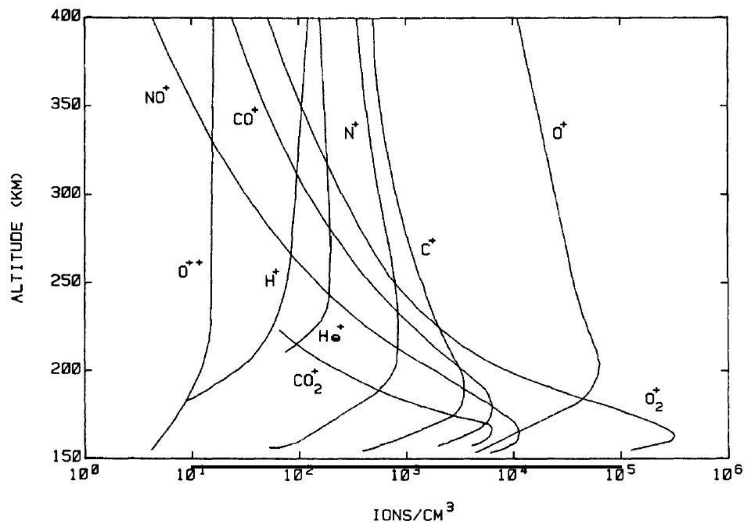

Fig. 3. An example set of dayside ion densities measured by the Pioneer Venus Orbiter Ion Mass Spectrometer instrument. Here, O_2^+ ions have the shape of a classical Chapman layer around 160 km, yet are overwhelmed by O^+ ions by 180 km. In the topside, the O^+ scale height is extremely large. Fig. 7-9 of Bauer et al. (1985).

3 – Measurements of the ionosphere of Venus

The ionosphere of Venus has been explored by a range of spacecraft and their instruments. The most significant are the Pioneer Venus Orbiter (Hunten et al., 1983) and Venus Express (Svedhem et al., 2007). Among the instruments onboard Pioneer Venus Orbiter were a neutral mass spectrometer, an ion mass spectrometer, a Langmuir probe, and a radio occultation investigation. The first three made in situ measurements (around solar maximum) along the spacecraft trajectory of the composition of the neutral atmosphere, the composition of the ionosphere, and the ionospheric electron density and temperature, respectively. The last one made remote sensing measurements (over a range of solar cycle conditions) of vertical profiles of ionospheric electron density. Pioneer Venus was a tremendously successful mission that characterized the entire atmosphere of Venus. Even today, the venerable in situ data from PVO constitute the most thorough sampling of an extra-terrestrial thermosphere and ionosphere ever performed. However, they possess one major limitation – they do not extend below spacecraft periapsis, which was usually maintained above 150 km to ensure a long mission lifetime. Hence the incredible in situ data rarely encompass the peak of the main layer of the ionosphere (which is sometimes called the V2 layer) and never encompass any lower regions (e.g. Figs 3 and 8, although they are atypical in encompassing the V2 peak, and Bauer et al., 1985). This is significant. Many interesting and important processes and phenomena occur in these regions. Properties of the main peak (its density, altitude, width) are the primary diagnostics of the overall behavior of the ionosphere. The lower ionospheric layer (Figs 4, 6, and 7), called the V1 layer by Patzold et al. (2007), that is maintained by photoionization by solar soft X-rays at 1-10 nm and associated electron impact ionization is barely addressed in the earlier literature (e.g. Cravens et al., 1981; Bauer et al., 1985; Kliore and Luhmann, 1991; Fox and Kliore, 1997), yet it is a major feature in the vertical structure of the ionosphere.

The entire vertical profile of the ionosphere was measured repeatedly by the remote sensing measurements of the Pioneer Venus Orbiter's radio occultation investigation. However, its 148 reduced electron density profiles from 1979-1989 (Kliore and Luhmann, 1991) were never distributed beyond a small team, which greatly limited their analysis and interpretation (if any readers have digital PVO electron density profiles, we would love to get copies of them). In fact, fewer than ten papers report the results of detailed hands-on analysis of this experiment's dayside data (Kliore et al., 1979; Cravens et al., 1981; Kim et al, 1989; Kliore and Mullen, 1989, 1990; Woo and Kliore, 1991; Kliore and Luhmann, 1991). Several additional papers synthesize the results of these primary papers in review articles or reference ionospheric models (Bauer et al., 1985, Brace and Kliore, 1991; Brace et al., 1997). This is a small number of primary publications in the context of Venus science. Many other publications concerning the Venus ionosphere discuss these data, but only as far as incorporating the results of this handful of papers or analyzing the figures published therein. This dataset, despite its age, has not been fully exploited yet, and so scientific analyses of radio occultation profiles of the Venus ionosphere remain potentially valuable today.

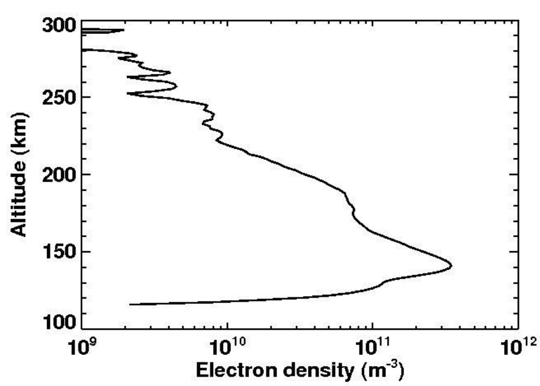

Fig 4. An example dayside electron density profile from Venus Express. The V2 layer is at 140 km and the V1 region is visible as a ledge at 120 km. The bulge at 190 km may be connected with a change in ion composition.

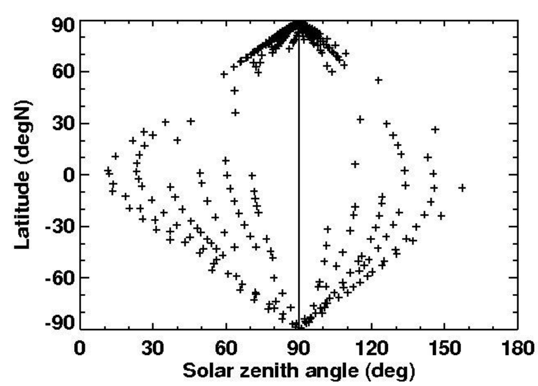

Fig 5. Latitude and solar zenith angle coverage of the >300 Venus Express electron density profiles. Dayside data have solar zenith angles less than 90 degrees (indicated by the vertical line).

Venus Express is a European Space Agency mission that arrived in orbit around Venus in 2006 and continues to operate today. Its radio occultation experiment, VeRa, has obtained over three hundred vertical profiles of ionospheric electron density. However, few scientific discoveries have originated from the VEX electron density profiles so far (the only two peer-reviewed papers that feature them are Patzold et al., 2007, 2009). One contributing factor is that Germany, home nation of the VeRa team leaders, does not support VEX ("ESA politics and processes" is the simplest explanation), so the radio occultation team must "leverage" resources from other projects (mainly the Mars Express and Rosetta radio science instruments) to get anything done at Venus. Another factor lies in the experiment leaders' lack of enthusiasm for making less-than-perfectly processed data publicly available – and data are never perfectly processed. PI Withers is an unfunded Co-Investigator on the VeRa team and therefore has access to all reduced electron density profiles. He is also a Co-Investigator for the radio occultation experiment on Mars Express, which is essentially run by the same team as for Venus Express. These electron density profiles from Venus Express are scientifically valuable because they have excellent vertical resolution (~1 km, a fraction of the neutral scale height), have excellent accuracy (~10^9 m^{-3}), and, unlike the in situ data of Pioneer Venus Orbiter, span the entire vertical extent of the ionosphere.

4 – Outline of proposal

The goal of this proposal is to explore the vertical structure of the ionosphere of Venus in order to better understand how the processes that maintain and shape planetary ionospheres operate at Venus and the other terrestrial planets. We shall investigate VEX radio occultation electron density profiles, augmented by the use of archived in situ ionospheric data from Pioneer Venus Orbiter and numerical simulations.

In situ Pioneer Venus Orbiter data provide only a coarse view of ionospheric vertical structure by comparison to radio occultation data, as can be seen by comparing Figs 3 and 8 to Figs 4, 6 and 7. We intend to determine what the fine-scale structure of the ionosphere is, meaning detailed characterization of the shapes of its main features, and then to elucidate how that structure is influenced by ionospheric processes and conditions in the background atmosphere. We want to understand how plasma composition, temperature, and density are related, with a keen focus on whether the radio occultation data show signatures of important changes in plasma composition and temperature. If so, then the radio occultation electron density data can provide valuable diagnostics of how the plasma composition and temperature vary, which is usually beyond the scope of remote sensing instruments.

We shall begin by surveying the set of VEX radio occultation electron density profiles (**Task A: Data analysis**). This is a basic starting point for any new dataset, yet no such overview paper (e.g., the "first year's results or "completion of prime mission" papers that are commonly generated by spacecraft instrument) has yet been published on these data. As described in Section 5, we have developed a suite of questions to be addressed. Many of these build upon our past and current studies of the ionosphere of Mars, which is very similar to that of Venus.

Next, we shall compare the VEX radio occultation electron density profiles to archived in situ ionospheric data from Pioneer Venus Orbiter (**Task B: Comparisons between Venus Express and Pioneer Venus data**). The in situ data products include plasma density (but with worse vertical resolution than the VEX profiles), plasma composition, and electron temperature. The lack of complementary composition and temperature measurements is usually the bane of anyone trying to interpret radio occultation electron density profiles in isolation. Composition controls the major chemical pathways and temperature controls key reaction rates.

Then we shall adapt an existing model of the ionosphere of Mars to Venus conditions and use it to reproduce the VEX radio occultation electron density profiles, especially the poorly-studied V1 layer (**Task C: Simulations**). By optimizing model inputs in order to reproduce individual profiles, we can study how variability in the Sun and neutral atmosphere lead to variability in ionospheric observations. Most previous work on reproducing ionospheric observations has focused on reproducing average observations, rather than exploring the significance of variations about that average or background state.

Finally, we shall compare the results of these **Tasks** to similar work at Mars that is currently underway in Professor Withers's research group (**Task D: Comparison of Venus and Mars**). By identifying which trends and features are common to both planets and which are unique to a single planet, we can begin to address the reasons why. This can focus attention on understanding the processes at work and why they operate the way they do.

5 – Task A: Data analysis

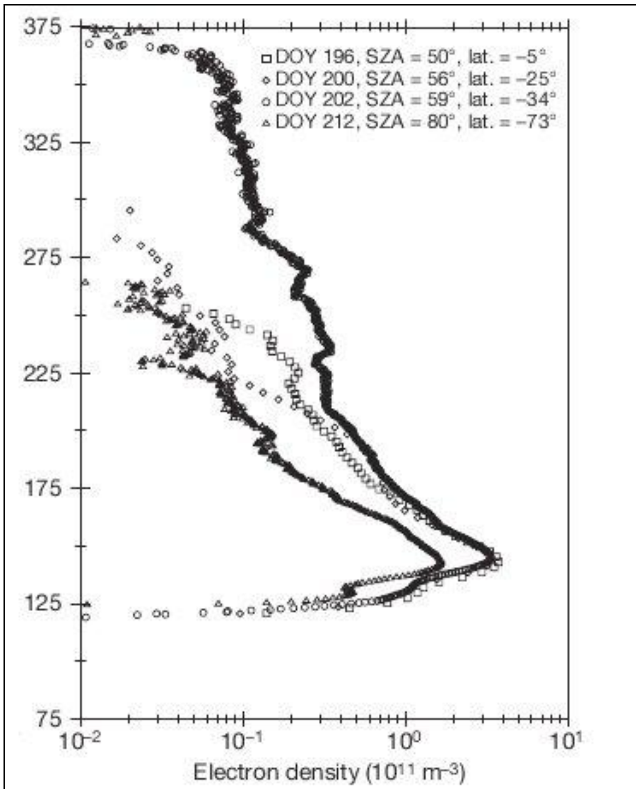

Fig 6. Four electron density profiles from VEX. The vertical axis is altitude in km. The three profiles with similar peak electron densities have solar zenith angles of ~55^o. The other profile has a solar zenith angle of 80^o. There are substantial differences between the three profiles at 55^o above 200 km. Figure 4a of Patzold et al. (2007).

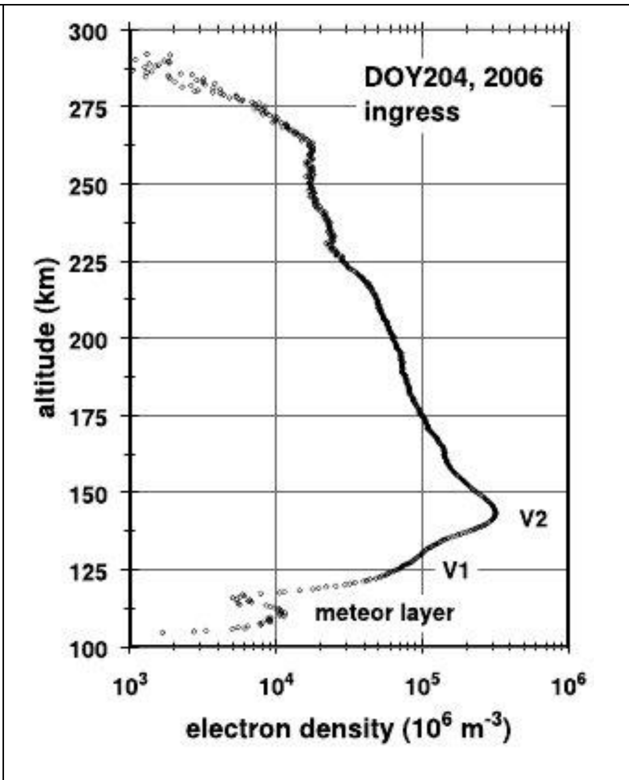

Fig 7. An electron density profile from VEX (solar zenith angle = 63^o). The ionopause is clearly visible around 260 km. A layer of meteoric plasma, here at 110 km, is sporadically present in such profiles. Comparison of Figs 4, 6, and 7 shows how variable the properties of the V1 layer are. Figure 1a of Patzold et al. (2009)

Task A is designed to study basic trends in several major features of the vertical structure of the Venus ionosphere, which is shown in Figs 6 and 7. Figs 4 and 5 demonstrate that we have access to the VEX radio occultation electron density profiles and are able to use and manipulate them.

The **Objectives** of **Task A** are:
Obj. A.1 To explore the properties of the lower ionosphere
Obj. A.2 To explore the properties of the main layer of the ionosphere
Obj. A.3 To explore the properties of the topside region of the ionosphere

These **Objectives** will be met by completion of the following **Investigations**:
Inv. A.1 Determine the peak electron density, altitude, width, and shape of the V1 layer and how they vary (**Obj. A.1**)
Inv. A.2 Characterize the peak electron density, altitude, width, and shape of the meteoric layer, how they vary, and how the layer's occurrence rate varies (**Obj. A.1**)
Inv. A.3 Characterize the shape of the V2 layer, including quantitative metrics of how closely it matches an idealized Chapman layer and how the neutral scale height inferred from its width corresponds to other observations and models (**Obj. A.2**)
Inv. A.4 Use variations in the altitude of peak electron density, which occurs at an optical depth of unity for EUV photons, to characterize how a fixed pressure level in the thermosphere depends on solar flux, solar zenith angle, local time, and latitude (**Obj. A.2**)
Inv. A.5 Determine how peak electron density depends on ionizing solar irradiance by using a range of different metrics for ionizing solar radiation (**Obj. A.2**)
Inv. A.6 Characterize the bulge in electron density at ~180 km that is so prominent in some profiles (e.g. Fig 4), but not in others (e.g. Figs 6-7), and investigate whether it is connected to changes in ion composition or other properties (**Obj. A.3**)
Inv. A.7 Characterize the ionopause altitude and its dependence on solar conditions (**Obj. A.3**)
Inv. A.8 Search for responses in ionospheric properties, such as topside scale height or structure, to individual solar events (**Obj. A.3**)
Inv. A.9 Characterize the shape and structure of the topside ionosphere, such as waviness, scale height, and any identifiable regions that can be classified (**Obj. A.3**)

Inv. A.1 will be the first survey of the characteristics of the V1 layer. Note how only one profile in Figs 4, 6, and 7, namely the 80^{o} profile in Fig 6, shows a V1 layer with a sharp local maximum, while the rest show merely ledges. Patzold et al. (2009) reported a preliminary analysis of meteoric layers, but a comprehensive study like that of Withers et al. (2008) for Mars awaits the completion of **Inv. A.2**. The properties of an idealized Chapman-like ionospheric layer (height, density, width) satisfy several simple relationships involving solar flux and solar zenith angle (Withers, 2009). Whether or not the Venus ionosphere can or should be considered Chapman-like is currently debated (e.g. Fox, 2007). These points will be explored in **Inv. A.3-A.5**. Of particular interest is the fact that peak electron density depends on solar flux proxies to the power 0.3-0.4 (Fox and Kliore, 1997), rater than the 0.5 expected for a photochemically-controlled molecular ion ionosphere. The disagreement between this exponent and 0.5 is inconsistent with more general principles than just idealized Chapman theory. Does this arise from the use of inappropriate solar flux proxies? The ubiquitous F10.7 index arose from terrestrial studies, yet the ionization potentials of O_2/N_2 (Earth) are around 100 nm and that of

CO_2 (Venus) is around 90 nm. Substantial solar energy is emitted between these wavelengths. We shall use solar spectra (Chamberlin et al., 2007, 2008a, b) to estimate the actual ionizing flux at Venus. The ionopause was studied in PVO data by many authors; in **Inv. A.7** we shall explore how it behaves during an unusually deep and prolonged solar minimum.

6 – Task B: Comparisons between Venus Express and Pioneer Venus Orbiter data

In situ data from the Pioneer Venus Orbiter mission are archived at the NASA Planetary Data System (PDS). For a mission that began in 1979, the quality of the archive is outstanding. Data products are easy to read and include scientifically useful quantities, not just raw counts. Fig 8 shows ion composition data from the ion mass spectrometer (OIMS) instrument and Fig 9 shows electron temperature and electron density data from the Langmuir probe (OETP) instrument. The data were not smoothed or processed in any way between our acquisition of them from the PDS archives and the generation of these images. **Task B** is designed to use the diverse types of Pioneer Venus Orbiter in situ data to complement the Venus Express electron density profiles. We shall pay attention to potential differences in solar conditions between the two epochs.

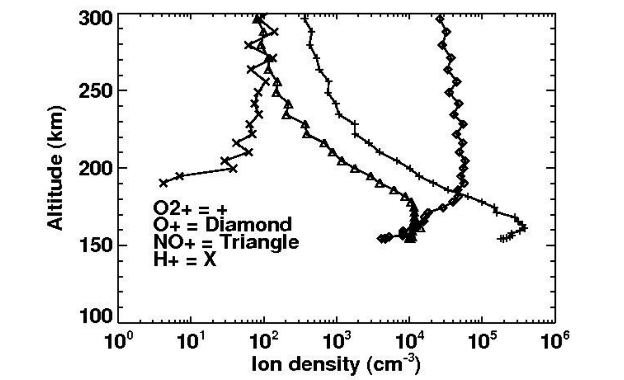

Fig 8. Selected ion composition data (ion mass spectrometer) from the inbound leg of PVO orbit 12. The O^+/O_2^+ transition is clear at 180 km. Data from PDS.

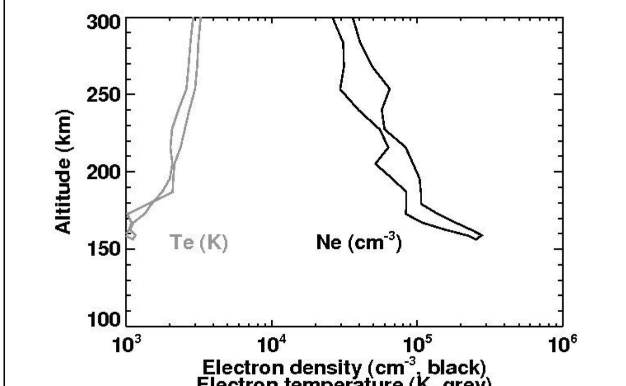

Fig 9. Electron density and temperature data (Langmuir probe) from inbound and outbound legs of PVO orbit 12. Temperatures increase substantially by 200 km. Data from PDS.

The **Objectives** of **Task B** are:
Obj. B.1 To compare VEX radio occultation electron densities to PVO plasma density data
Obj. B.2 To interpret VEX radio occultation electron density profiles using data on other ionospheric properties from Pioneer Venus Orbiter measurements under comparable conditions

These **Objectives** will be met by completion of the following **Investigations**:
Inv. B.1 Acquisition of all relevant archived Pioneer Venus Orbiter data and development of computer programs to organize and manipulate these datasets (**Obj. B.1, B.2**)
Inv. B.2 Generation of empirical models of plasma density for each dataset (such models already exist for some Pioneer Venus Orbiter datasets, e.g. Theis et al., 1980) (**Obj. B.1**)
Inv. B.3 Comparison of Venus Express and Pioneer Venus plasma density data (**Obj. B.1**)
Inv. B.4 Comparison of Venus Express observations of a bulge in electron density near 180 km (**Inv. A.6**) to Pioneer Venus Orbiter plasma composition and electron temperature data (**Obj. B.2**)

Inv. B.5 Comparison of Venus Express observations of the shape of the V2 layer (**Inv. A.3**) to Pioneer Venus Orbiter plasma composition, neutral composition, and electron temperature data (**Obj. B.2**)
Inv. B.6 Comparison of Venus Express observations of the structure of the topside ionosphere (**Inv. A.9**) to Pioneer Venus Orbiter plasma composition and electron temperature data (**Obj. B.2**)

The main ionospheric peak (V2 layer) and bulge (180 km) occur in VEX radio occultation electron density profiles at altitudes where Pioneer Venus data show major transitions in two critical ionospheric properties, ion composition and electron temperature (Figs 3, 8, 9; Taylor et al., 1985; Theis et al., 1980). The ion composition is dominated by O_2^+ at the V2 layer, but O^+ at higher altitudes. The electron temperature equals the cool neutral temperature at the V2 layer, but rises to thousands of Kelvin by 200 km altitude. Here in **Task B**, we shall investigate how the high vertical resolution, high formal precision ionospheric density measurements made by the VEX radio occultation instrument respond to these changes.

7 – Task C: Simulations

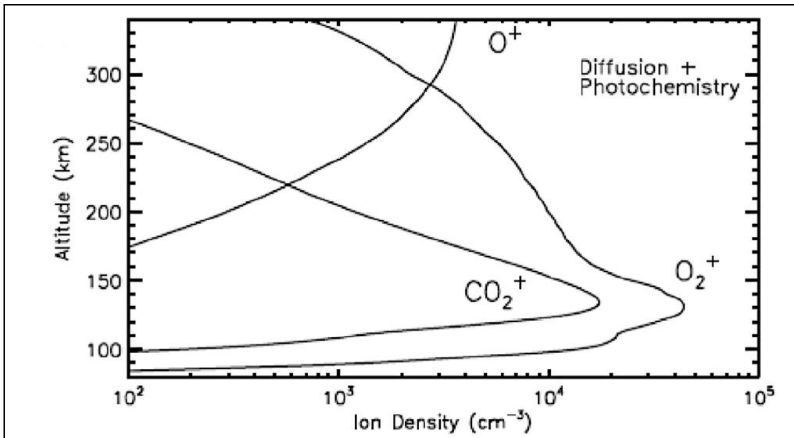

Fig 10. Simulation of the ionosphere of Mars. Density profiles for major ions at a solar zenith angle of 80°. The M2 layer is at 130 km and the smaller M1 region is visible as a ledge at 110 km. Note that O_2^+ is the dominant species far above the main peak, unlike at Venus. Figure 15c of Mendillo et al. (2011).

Numerical models are an essential tool for interpreting observations. They can cover times, positions, and conditions that are not sampled by sparse observations. They also enable more direct investigations of individual processes and the roles of individual properties than is permitted by a single type of observation. We anticipate that the results of **Tasks A and B** will still leave unanswered questions about how the ionosphere of Venus works. In order to address those, here in **Task C** we will adapt an existing model of the ionosphere of Mars to Venus conditions. Now, it is true that other models of the ionosphere of Venus already exist. However, we require the capability to adjust model inputs and explore model output in detail, which cannot be accomplished by the perusal of figures published by other modelers. The niche we are aiming for is the investigation of what can be learned from variations in observed properties.

Boston University has recently developed a 1-D Mars ionospheric model (Martinis et al., 2003; Mendillo et al., 2003, 2011; Lollo et al., 2011; Matta et al., 2011). Sample output is shown in Fig 10. Publications have focused on the effects of solar variability on electron density profiles at Mars, with timescales that include the 11-year solar cycle, the 28-day solar rotation, day-to-day variability, and hour-long solar flares. Plasma is produced by photoionization and electron impact ionization, undergoes chemical reactions with neutral species, is transported vertically under the influences of pressure gradients and gravity, and is destroyed by dissociative recombination of molecular ions. A detailed discussion of the model can be found in Mendillo et al. (2011).

The **Objectives** of **Task C** are:
Obj. C.1 To convert an existing model of the ionosphere of Mars to Venus conditions
Obj. C.2 To validate the converted model at Venus
Obj. C.3 To apply the model to interpret VEX radio occultation electron density profiles

These **Objectives** will be met by completion of the following **Investigations**:
Inv. C.1 Adjustment of the representation in the ionospheric model of the neutral atmosphere (Hedin et al., 1983; Krasnopolsky and Parshev, 1983; Yung and DeMore, 1999, Bougher et al., 1997, 2002; Bougher, 1995), electron temperature (Theis et al., 1980), electron impact ionization (Simon Wedlund et al., 2011; Mendillo et al., 2011), boundary conditions, and basic planetary properties like distance from Sun and gravitational acceleration (**Obj. C.1**)
Inv. C.2 Verification that the converted model adequately reproduces the empirical models of plasma density and composition used in **Inv. B.2**, with modifications made to the model as necessary (**Obj. C.2**).
Inv. C.3 Analysis of the simulated V1 layer, which has been minimally studied by previous workers, and comparison against observations (**Obj. C.3**)
Inv. C.4 Analysis of how the shape of the V2 layer and conditions in nearby topside regions depend on the characteristics of the transitions in plasma composition and temperature that occur at these altitudes, with a focus on what can be inferred about these transitions from observed electron density profiles (**Obj. C.3**)
Inv. C.5 Reproduction of substantial variations in ionospheric observations obtained under similar conditions, such as those discussed around 200 km in Fig 6 (**Obj. C.3**)
Inv. C.6 Exploration of why peak electron density depends on typical solar flux proxies raised to the power 0.3-0.4, rather than 0.5 (**Inv. A.5**) (**Obj. C.3**)

<u>8 – Task D: Comparison of Venus and Mars</u>

Many workers have used the striking similarities between the ionospheres of Venus and Mars (Fig 11) as the basis for comparative studies (e.g. Bougher, 1995; Luhmann et al., 1992). Here in **Task D**, we follow in those well-trodden footsteps.

The **Objective** of **Task D** is:
Obj. D.1 To better understand terrestrial planet ionospheres by comparative studies of the ionospheres of Venus and Mars

This **Objective** will be met by completion of the following **Investigations**:
Inv. D.1 Analysis of whether electron temperatures at Mars, which are poorly constrained by observations, can be estimated by analogy to, or rescaling of, Pioneer Venus electron temperature observations, such as by adapting a functional form that is valid at Venus (**Obj. D.1**)
Inv. D.2 Identification of similarities/differences between trends involving the related V1 and M1 ionospheric layers and the development of hypotheses to explain them (**Obj. D.1**)

Inv. D.3 Search for topside layering at Venus analogous to that found at Mars by Kopf et al. (2008) (**Obj. D.1**)
Inv. D.4 Analysis of sets of near-simultaneous ionospheric observations by Venus Express and Mars Express to explore whether any ionospheric features respond similarly to changes in solar forcing (**Obj. D.1**)

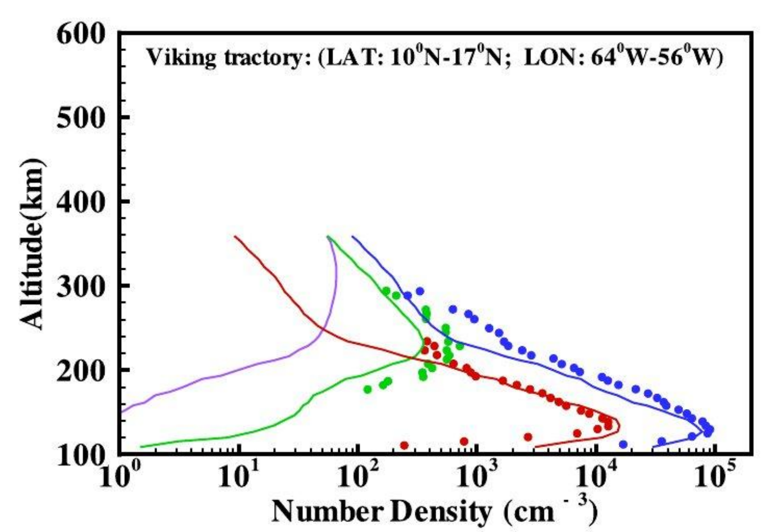

Fig 11. Observed and simulated Viking Lander 1 ion densities. Blue is O_2^+, red is CO_2^+, green is O^+, and purple is H^+. O^+ is significant above 200 km. Similar to Figs 3 and 8 for Venus, O_2^+ dominates at low altitudes, CO_2^+ is a steady small fraction of O_2^+ densities, and O^+ becomes important at higher altitude. Unlike at Venus, O^+ is not clearly the dominant ion at 200 km and above. The plasma scale height is much smaller at Mars than Venus. Figure 8d of Ma et al. (2004).

<u>9 – Broader impacts of proposed project</u>

The scope and design of this proposed project results in several noteworthy broader impacts, including the involvement of high school students, undergraduate students, and school teachers in frontline scientific research, the training of the next generation of professional-level scientific reseachers, the production of scientific articles aimed at wide audiences, international collaboration, and the analysis of a woefully underutilized spacecraft dataset. Much of the technical research to be conducted in this project will be performed by graduate students who will also have major responsibilities for ensuring that this work has significant broader impacts.

Boston University has a well-established program that brings rising high school seniors onto campus and into a professor's laboratory over a summer. This occurs at no expense to the professors or their departments. These students will generally head to Stanford, MIT, or comparable institutions for their undergraduate degrees, so they are highly talented and highly motivated. We will invite two high school students to conduct focused, well-defined research activities with us in the summer of Year 2. They will be mentored closely by the graduate students, who will learn leadership and mentoring skills from this experience. PI Withers will provide oversight and ensure that the high school students find their time commitment productive. He will also work with the graduate students to define their projects.

Undergraduate students (nominally two) will be employed for the duration of this project. Their role is to conduct some of the more mundane aspects of the proposed work. For **Task A**, this includes supporting **Inv. A.1, A.2, and A.7**. For **Task B**, this includes supporting **Inv. B.1 and B.3**. For **Task C**, this includes supporting **Inv. C.4 and C.6**. For **Task D**, this includes supporting **Inv. D.3 and D.4**. The undergraduate students will each be paired with a graduate student for day-to-day activities, who will again learn leadership and mentoring skills from this experience, although strategic direction and supervision will be provided by PI Withers.

Several existing Boston University programs bring teachers onto campus and expose them to the practice of research. We will leverage these to bring two school teachers into the laboratory to conduct small-scale research activities alongside the graduate students in the summer of Year 3. These activities will be designed to support the **Investigations** of this proposed project, with their precise definition depending on our progress by that time. We want teachers to wrestle with real observations of conditions in planetary atmospheres so that they can develop an appreciation for the actual, not idealized, process of scientific research and plan ways to integrate similar activities into their classrooms. The realization that science is messy and uncertain, rather than unassailable and immutable facts listed in textbooks, is tremendously important for keeping children engaged in science as students and later as active citizens.

The graduate students who we plan to involve in this project are currently working on the ionosphere of Mars. As such, they will need to conduct extensive literature reviews in preparation for transitioning to studies of Venus (already initiated as a result of this and other proposals). As a byproduct of this background reading, they will synthesize the current literature into a review article for publication in a journal like Advances in Space Research. This will provide the scientific community with a useful resource.

The graduate students will also apply their knowledge of the ionospheres of Venus and Mars to revise relevant Wikipedia articles. Wikipedia articles, even those on technical topics, are read by more readers than any scientific papers and the current Wikipedia articles on these topics are incomplete, poorly-written, and supported by few references. There is substantial room for improvement. In addition, the process of justifying revisions to other strong-willed Wikipedia contributors will be a worthwhile educational experience for the graduate students.

Finally, this project involves continued collaborations with the European science team of the Venus Express radio occultation instrument and represents one of the few ways in which this instrument’s data and their implications will reach the peer-reviewed literature. We cannot receive NASA support to study these data since NASA’s data analysis programs have firm policies excluding the analysis of data that are not publicly available. We would dearly love to see these data made public, but if that is not possible (and it has not been possible yet, despite many people’s efforts) then funding proposals like this might be an effective way of ensuring that the data are not completely forgotten and ignored.

At the conclusion of this project, we will have conducted a discovery-mode survey of the unexplored Venus Express ionospheric observations, compared them to complementary Pioneer Venus Orbiter observations, developed and applied a numerical model to study these observations, and used Venus-Mars comparisons to untangle the physical causes for similarities and differences in their ionospheres.

The products of this proposed project will include a peer-reviewed review article on the ionosphere of Venus in a journal like Advances in Space Research (assembled by PI Withers) and a peer-reviewed research article in a journal like Journal of Geophysical Research or Icarus for each of **Tasks A to D** (each led by a graduate student). The work of the graduate students will also be incorporated into their PhD dissertations and the work of the undergraduate students may also be synthesized in their senior theses.

10 – Personnel

This investigation will be carried out by PI Paul Withers, Boston University students, and Collaborator Steve Bougher (University of Michigan).

PI Withers has completed a range of studies on the ionosphere of Mars, including the effects of solar energetic particle events, meteoroid influx, crustal fields (both observational and theoretical), solar flares, and other solar variations (Withers and Mendillo, 2005; Withers et al., 2005, 2008; Withers, 2008, 2009, 2011; Mendillo et al., 2006; Opgenoorth et al., 2010; Lillis et al., 2010). He has also made significant contributions to the development of Boston University's 1-D Mars Ionosphere Model (Mendillo et al., 2011; Lollo et al., 2011; Matta et al., 2011, and many conference presentations by Withers). This is the model that will be adapted to Venus in **Task C**. He has previously studied the ionosphere of Venus as well (Paetzold et al., 2009). He will mentor two graduate students and two undergraduate students, who will conduct the day-to-day work on this project. We plan to involve two graduate students, Katy Fallows and Zachary Girazian, in this project. Both passed their comprehensive exams in their first year (only about 20% of students do so) and have almost completed their required courses.

Second year graduate student Katy Fallows is examining the shape and behavior of the lower layer of the ionosphere of Mars (analogous to the Venus V1 layer) using Mars Global Surveyor radio occultation data. She has developed the first technique to automatically characterize the main properties of this layer, which enables many comparisons between it, the main layer, and ionospheric layers on other planets. These studies will constrain the physical processes that maintain this enigmatic plasma layer. She is also performing the first simulations of the response of Mars's ionosphere to a solar flare (Lollo et al., 2011). Lower layer densities increase substantially as the solar X-ray flux surges. She has compared data and models to improve simulations of how electron impact ionization processes produce most of the plasma in this layer.

Second year graduate student Zachary Girazian is examining the shape and behavior of the main layer of the ionosphere of Mars (analogous to the Venus V2 layer) using Mars Express radio occultation data (Girazian et al., 2011). He has identified several unusual features that are sporadically present around this layer, which highlight gaps in current understanding, and he has shown that the layer's shape is usually well-represented by an idealized Chapman layer. The degree to which this region of the ionosphere can be approximated by Chapman theory is hotly debated, as is whether the success of this theory is coincidental or not.

The Boston University Astronomy Department awards about a dozen undergraduate degrees each year, and most of these students participate in a professor's research group for some fraction of their time at school. Undergraduates in other scientific and engineering departments are also interested in being paid to conduct research in astronomy (research has to be more interesting than manning a reception desk). Professor Withers receives unsolicited emails from interested students a few times per semester. As he is currently teaching the first course taken by Astronomy freshmen, he is well placed to identify and hire the most promising undergraduates.

Collaborator Steve Bougher, Research Professor in the Atmospheric, Oceanic, and Space Sciences Department at the University of Michigan, studies planetary upper atmospheres and ionospheres. His main tools are physics-based climate models or thermospheric general circulation models (TGCMs). His Venus (Dickinson and Bougher, 1986, Bougher et al., 1986, 1988, 1997, 2002; Bougher, 1995) and Mars models are benchmarks in the field whose predictions are widely used by many researchers.

11 – Work plan

Professor Withers will be responsible for the success of this investigation and for compliance with all reporting requirements. He will mentor the graduate and undergraduate students and direct their activities. His funded effort is 1 month per year, but 40% of his time during the 9-month academic year is nominally available for research projects such as this one. We have requested annual funding for 12 months FTE of graduate student effort and 12 months FTE of undergraduate student effort. We plan that graduate students Katy Fallows and Zachary Girazian will each be supported half-time by this project and half-time on Mars-related projects supported by other external grants. That will ensure that they will become well-rounded scientists, rather than narrow specialists, and it will also ensure that comparisons between Venus and Mars are always on their minds. Katy Fallows, who is currently using the Mars ionospheric model, will work on **Tasks C and D**, while Zachary Girazian, who is currently analyzing Mars Express radio occultation electron density profiles, will work on **Tasks A and B**. We plan to hire two undergraduates to work on this project. One will work alongside Katy Fallows on **Tasks C and D**, while one will work alongside Zachary Girazian on **Tasks A and B**.

Collaborator Bougher will provide advice on the Venus ionosphere, thermosphere, and space environment interactions. He will also supply neutral atmospheric conditions from the Venus Thermospheric General Circulation Model (VTGCM) and contribute to the interpretation of the results of this project. Our interactions with him will occur via phone and email as needed, plus anticipated face-to-face meetings at conferences.

Table 1 outlines our planned distribution of effort by the student personnel. **Task A** will receive 9 months of graduate student effort and 9 months of undergraduate effort. **Task B** will receive 7 and 8 months, respectively. **Task C** will receive 9.5 and 9 months, respectively. **Task D** will receive 6.5 and 9 months, respectively. Professor Withers's funded and unfunded efforts will be focused on mentoring the students, planning, and contributing as appropriate to the publications (leading a review article, supporting the articles arising from the technical **Tasks**). We recognize that we have proposed to perform a substantial amount of work here and we have considered streamlining some aspects of this proposal to reduce the workload. In the end, we decided not to do so in order to maintain a coherent and comprehensive intellectual plan. If the reviewers feel that the proposed work plan is overambitious, we hope they will acknowledge that partial completion of it would still be worthwhile. In the event that our funded effort is not sufficient to accomplish all that we have proposed, we will scale back on **Tasks B and D**.

Activity	Katy Fallows	Zachary Girazian	Undergrad 1	Undergrad 2
Inv. A.1		0.5m in Y1		3m in Y1
Inv. A.2		0.5m in Y1		3m in Y1
Inv. A.3		1m in Y1		
Inv. A.4		1m in Y1		
Inv. A.5		1m in Y1		
Inv. A.6		1m in Y1		
Inv. A.7		0.5m in Y2		3m in Y2
Inv. A.8		1m in Y2		
Inv. A.9		1m in Y2		
Manuscript on Task A		1.5m in Y2		1m in Y2
Inv. B.1		0.5m in Y2		2m in Y2, 2m in Y3
Inv. B.2		1m in Y2		
Inv. B.3		1m in Y3		3m in Y3
Inv. B.4		1m in Y3		
Inv. B.5		1m in Y3		
Inv. B.6		1m in Y3		
Manuscript on Task B		1.5m in Y3		1m in Y3
Inv. C.1	1.5m in Y1			
Inv. C.2	1.5m in Y1			
Inv. C.3	1m in Y1, 1m in Y2			
Inv. C.4	0.5 m in Y1		4m in Y1	
Inv. C.5	2m in Y2			
Inv. C.6	0.5m in Y1		2m in Y1, 2m in Y2	
Manuscript on Task C	1.5m in Y2		1m in Y2	
Inv. D.1	0.5m in Y2, 1.5m in Y3			
Inv. D.2	2m in Y3			
Inv. D.3	0.5m in Y2		3m in Y2, 1m in Y3	
Inv. D.4	0.5m in Y3		4m in Y3	
Manuscript on Task D	1.5m in Y3		1m in Y3	
Review article	0.5m in Y1	0.5m in Y1		
High school students	0.5m in Y2	0.5m in Y2		
School teachers	0.5m in Y3	0.5m in Y3		
Wikipedia contributions	0.5m in Y1	0.5m in Y1		

Table 1. Outline of planned time commitments by named individuals. Read "1m in Y2" as "one month of effort in Year 2". Colors also indicate year, red=Y1, blue=Y2, black=Y3.