Relevance of *Rosetta* Noble Gas and Isotopic Measurements to Understanding the Origin and Evolution of Venus' Atmosphere

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Introduction:

Understanding the evolution terrestrial atmospheres is essential for evaluating how life emerged and thrived on Earth, but not apparently on present-day Venus or Mars. Extensive studies have been conducted for Earth [e.g. 1] and Mars [2], but Venus is the least understood [3]. Studying Venus' atmospheric history can determine: (1) the origin of volatiles; (2) the total initial abundance of volatiles; and (3) the outgassing history. Cometary observations of nitrogen isotope ratios constrained nitrogen origin and evolution for Mars [6], Titan [6,7,8], Pluto [5,9] and Triton. Now, cometary noble gas abundances and isotope ratios can help to understand Venus [4,5,6].

Volatile Sources:

The isotopic and noble gas abundances of the terrestrial planets likely resulted from a complex mix of gas absorbed directly from the protosolar nebula (PSN) and volatiles contributed by impact of planetesimals and comets formed at varying distances from the Sun. Solar values represent the bulk abundance of the PSN. Cometary and chondritic values provide information about solid materials and the variation of gas composition in the PSN [10]. Source composition is shown in Figs. 1-5.

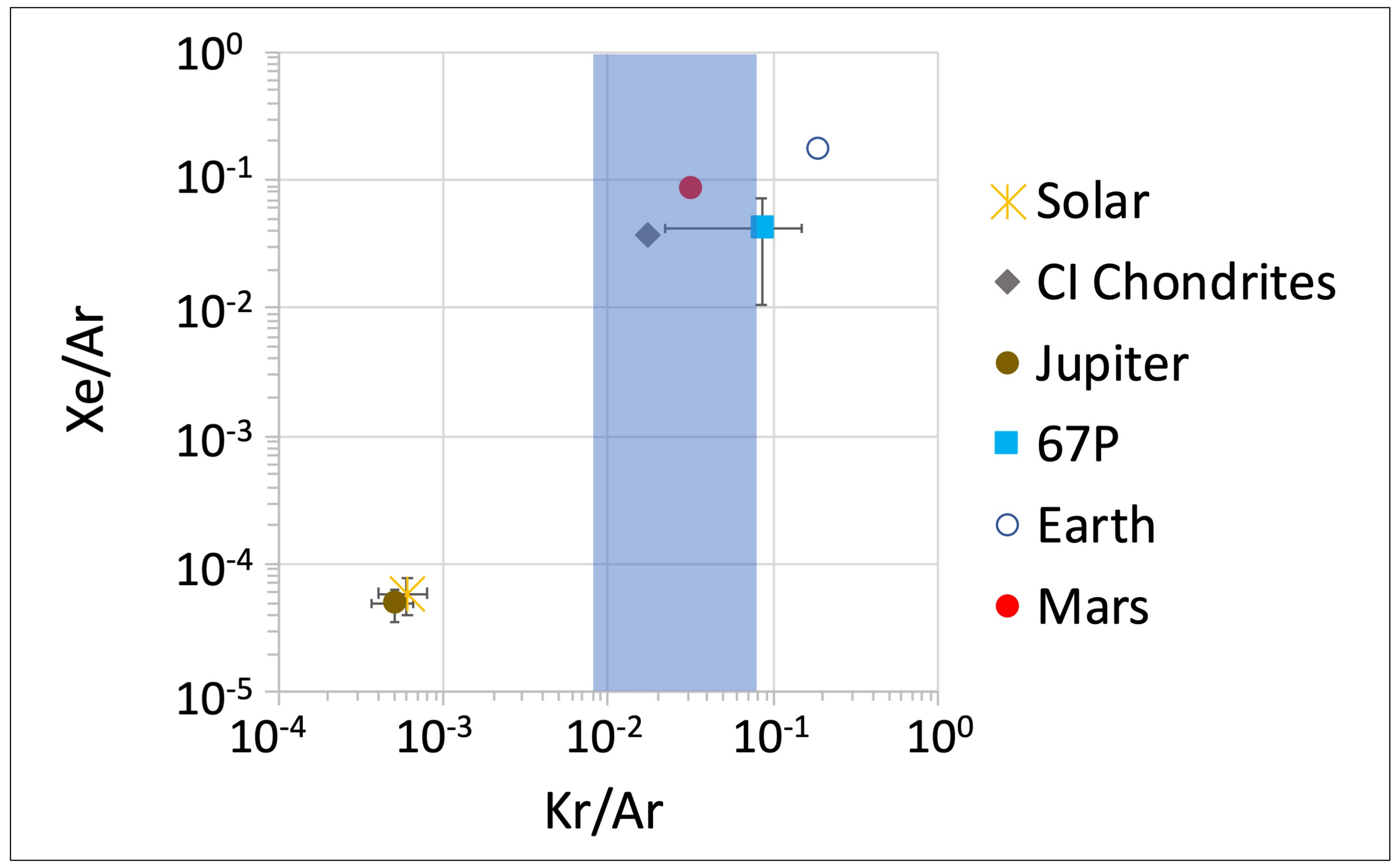

Figure 1 | Relative abundances of the two heaviest noble gases, krypton and xenon, compared to argon where observations are available [adapted from 6]. Jupiter is clearly solar while the analogs for the giant planet building blocks are supersolar in both krypton and xenon compared to argon by more than two orders of magnitude. The atmospheres of Mars and the Earth are similarly supersolar. Venus krypton measurements are shown as the shaded region [7] and indicate that Venus is supersolar, but closer to Mars and chondrites than to Earth and comets. Future measurements of krypton with smaller error bars, and observations of xenon will be highly valuable.

Observations:

Cometary and other observations of noble gas abundances and isotope ratios are compared to the current state of knowledge for Venus in Figs. 1-5.

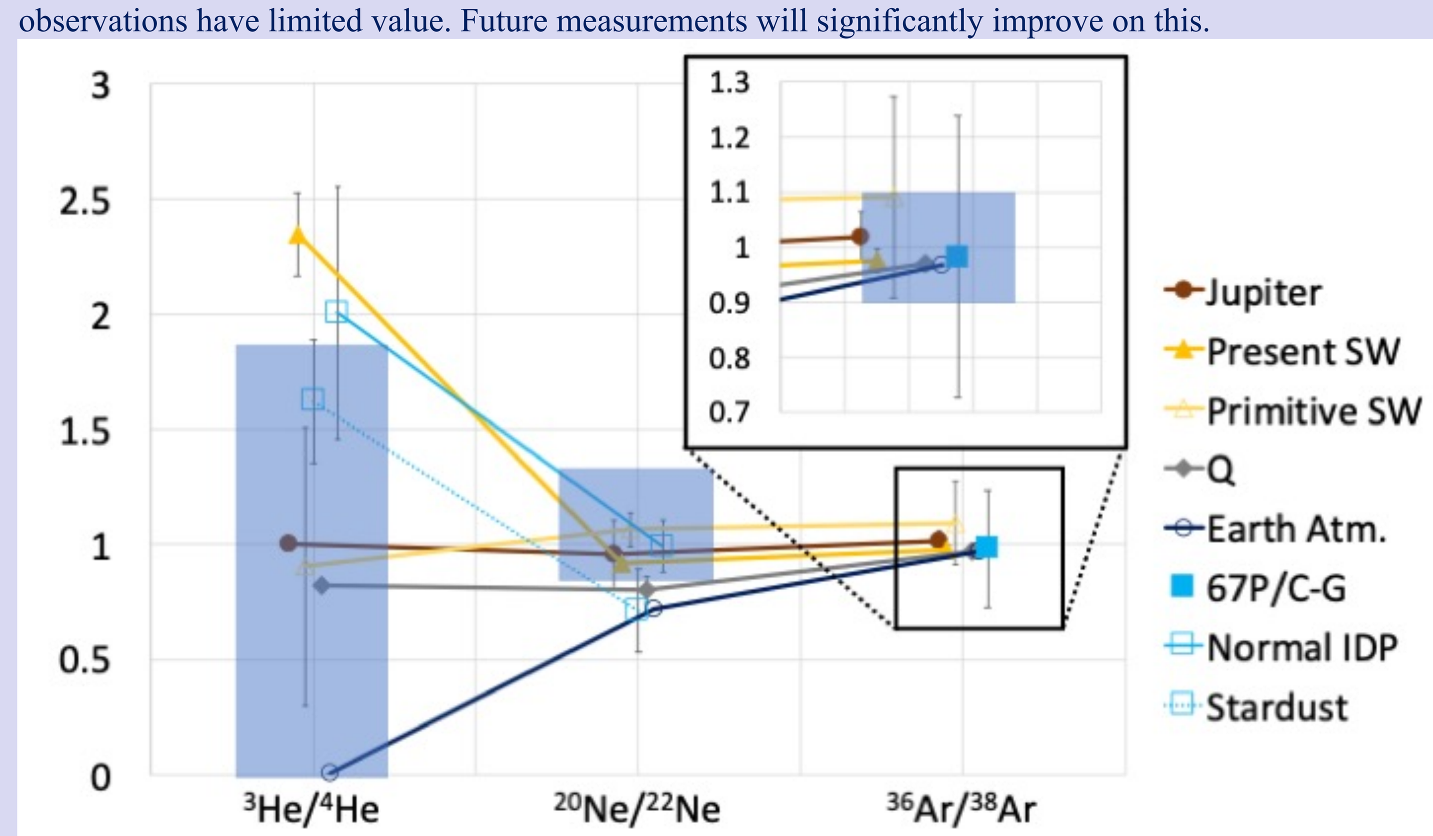

Figure 2 | Helium, neon and argon isotopes [adapted from 6]: Cometary abundances for argon are based on the *Rosetta* observations. Because *Rosetta* did not detect helium or neon, we use Interplanetary Dust Particle (IDP) measurements for the cometary values for these noble gases. Trapped gases in meteorites provide constraints on the PSN gases where the asteroids formed, designated as the "Q" values, as well as solar wind contributions from the primitive and current Sun. Observations for Venus [7] are shown in the blue shaded regions for comparison. The error bars are so large that the observations have limited value. Future measurements will significantly improve on this.

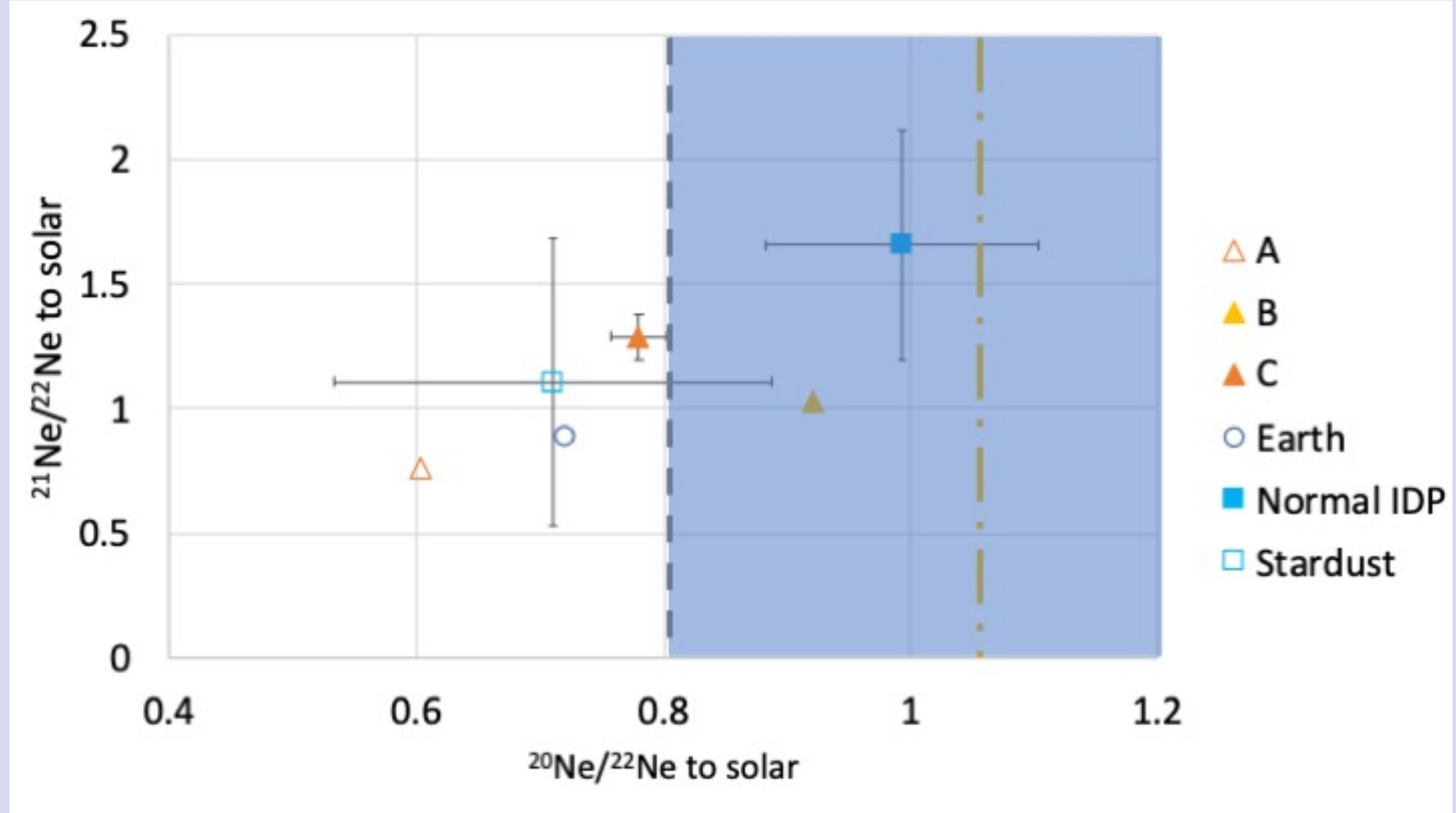

Figure 3 | Three-isotope plot for neon for available observations. The shaded blue region illustrates the range of values possible for ^{20}Ne/^{22}Ne for Venus. The gold dash-dot line is the ^{20}Ne/^{22}Ne for the primitive solar wind and the dashed gray line gives the ^{20}Ne/^{22}Ne value for phase Q. Three components for chondrites are shown here as A, B, and C. Component A is a strongly fractionated planetary-type component that is not well-constrained. Components B and C are of solar origin, where B is identified as the present-day solar wind and C is implanted solar wind from low energy solar flares.

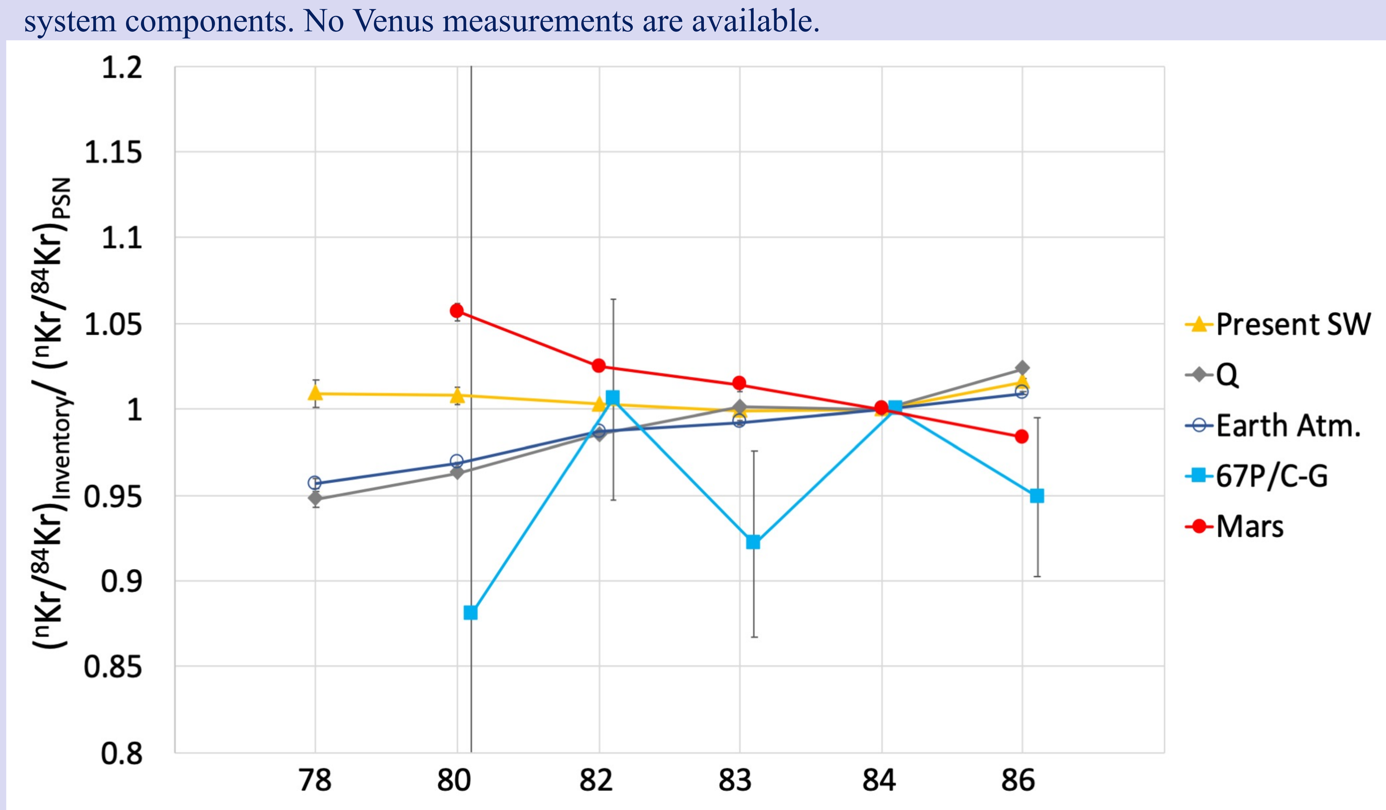

Figure 4 | Krypton isotopic composition of different solar system objects and reservoirs [6]: Data are normalized to the PSN composition and to ^{84}Kr. Error bars are generally within the symbols, except for 67P/C-G for which errors are about 5%, thus covering most krypton isotope variations of inner solar system components. No Venus measurements are available.

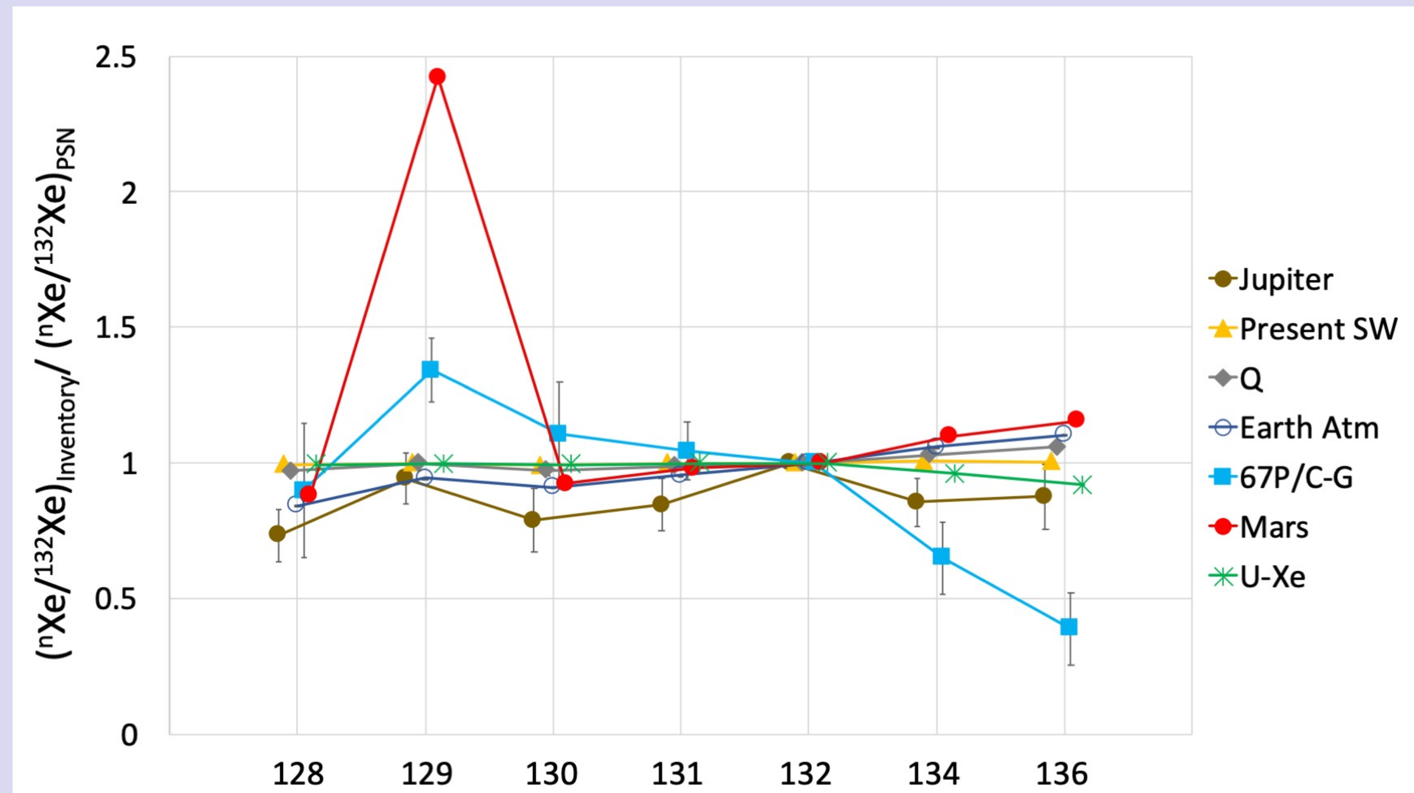

Figure 5 | Xenon isotopic composition of different solar system objects and reservoirs [6]: Data are normalized to the PSN composition and to ^{132}Xe. Error bars are generally within the symbols, except for Jupiter and 67P/C-G. U-Xe is thought to be a primordial xenon component, different from chondritic, that is proposed to have been delivered to the early Earth atmosphere. No Venus measurements are available.

Discussion:

- Constraining atmospheric evolution first requires an understanding of the composition of the potential sources for noble gases.
- New cometary measurements from *Rosetta* help to complete the inventory of observations for potential volatile sources and are illustrated here in Figs. 1-5.
- Helium and xenon isotopes provide the most diagnostic measurement for source materials because the wide range of values throughout the solar system can be used to identify sources of volatiles for Venus [6].
- Future measurements by upcoming missions will dramatically improve our understanding of volatile delivery and evolution for the terrestrial planets.

References:

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Acknowledgements: K.E.M. acknowledges support from NASA RDAP 80NSSC19K1306.