MARTIAN MEANDERS: WAVELENGTH-WIDTH SCALING AND FLOW DURATION. H. Gregoire-Mazzocco, *Dipartimento IMAGE, Universita di Padova, via Loredan 20, I-35131 Padova, Italy*[1],*(mazzocco@idra.unipd.it)*, T.F. Stepinski, *Lunar and Planetary Institute, Houston TX 77058-1113, USA*[2], *(tom@lpi.usra.edu)*, P.J. McGovern[2], S. Lanzoni[1], A. Frascati[1], A. Rinaldo[1].

Abstract. Morphometric analysis of 117 Martian meanders reveals a linear wavelength/width scaling with a coefficient $k \sim 10$ similar to what is observed in terrestrial rivers. The scaling coefficient is used to provide estimates of flow velocity and discharge based exclusively on measurable quantities. Numerical simulations of channel evolution are used to determine a duration of fluvial activity in a channel from the value of its average sinuosity. Application to Nirgal Vallis yields flow duration ~ 200 yrs.

Introduction. Terrestrial rivers and other channeled flows have a tendency to meander. Two important empirical results have been made about terrestrial meanders. First, scaling is observed between various meander parameters. In particular, there is a remarkable proportionality between meander cartesian wavelength and channel width; the wavelength is $k = k_{terr} = 7 - 12$ times the channel width [*Leopold and Wolman*(1960)]. This proportionality is valid over vastly different conditions and range of width scales. Second, meander evolution increases its sinuosity; initially straight river develops ever more pronounced bends until cutoffs occur. Models of meandering dynamics have been developed [*Ikeda et al.*(1981); *Seminara et al.*(2001); *Edwards and Smith*(2002)] to provide a theoretical underpinning of these observations. These models reveal an existence of the characteristic scale for the meandering wavelength that depends linearly on the channel width explaining the observed proportionality. The models also provide the means of estimating a duration of fluvial activity in a channel from the degree of its sinuosity.

Sinuous channels are observed on the surface of Mars. Their length scales vary from ~ 1000 km for outflow channels to ~ 1 km for interior channels in valley. *Weihaupt* (1974) first suggested that sinuous character of Martian channels is due to the terrestrial-like meandaring process. Using Viking images, *Kereszturi* (2001) measured parameters of 140 meanders in valley networks and outflow channels in a search of wavelength/width scaling. Most recently *Moore et al.* (2003) and *Irwin et al.* (2005) reported the presence of the wavelength/width scaling in small, 1-10 km scale, channels. The purpose of this study is as follows. First, using a systematic method of meander extraction, to examine the issue of the wavelength/width scaling in Martian channels. Second, taking advantage of this scaling to estimate channel's flow velocity and discharge directly from stress balance equation using only directly observable quantities. Third, using a computer simulation of meandering dynamics to estimate the duration of fluvial activity.

Data and Methods. We use digital elevation models (DEMs) given by the 128 pixels/degree Mission Experiment Gridded Data Records (MEGDR) [*Smith et al.*(2003)] to computationally extract 8 large Martian channels, their 93 individual meanders, and meanders' morphometric parameters. The 8 large channels are: Granicus Vallis (137^{o}E, 29^o.7, 19), Indus Vallis (38^o.7E, 19^o.1, 6), Ma'adim Vallis (177^o.3E, -21^o.6, 7), Nirgal Vallis (318^{o}E, -28^o.2, 18), Dao Vallis (87^o.8E, -38^o.4, 8), Shalbatana Vallis (317^o.9E, 7^o.8, 11), Hrad Vallis I (135^o.3E, 38^o.4, 12), and Hrad Vallis II (135^o.3E, 38^o.4, 12). The numbers in brackets are coordinates followed by the number of identified meanders in a channel. In order to include some smaller scale meanders in the analysis, four additional channels were identified in 57 m/pixel Viking images and divided into 24 individual meanders. Fig.1A shows an image of Nirgal Vallis from which we have extracted 18 meanders.

Meanders' parameters are described on Fig.1B. A meander is defined as a portion of the channel containing three consecutive inflection points of channel's centerline $\Gamma(s)$. Each meander is characterized by: 1) the intrinsic wavelength, L_s, computed along the s-coordinate – a distance calculated downstream along the flow; 2) the cartesian wavelength, L, defined by the distance between the initial and the terminal points of the meander; 3) the channel's half-width, B, calculated as an average over the meander wavelength. The degree of meandering is measured by the dimensional parameter "sinuosity," defined as $\sigma = L_s/L$.

Numerical simulation of channel evolution was set up in order to establish quantitatively the dependence of $\langle\sigma\rangle$ and $\langle(\sigma - \langle\sigma\rangle)^2\rangle^{1/2}$ on flow duration. The initial condition is a straight channel subject to slight and random perturbations. The planimetric development of $\Gamma(s,t)$ serves as a proxy for channel evolution. The evolving channel develops meanders with a characteristic wavelength that is maintained during the evolution, however, average sinuosity of meanders increases with time. This feature allows using $\langle\sigma\rangle$ as a proxy of flow duration.

Results. Fig.1c shows the $(2B, L)$ data for 117 Martian meanders superimposed on the terrestrial data. It is clear that wavelength/width scaling in Martian bends conforms to the analogous scaling in terrestrial meanders. The values of k in Martian meanders range from 3 to 40, with $\langle k\rangle = 12$ and $\langle(k - \langle k\rangle)^2\rangle^{1/2} = 8$.

The scaling coefficient k, which can be directly measured from Fig.1C, can also be expressed in terms of $C_f\beta$, a product of dimensionless friction coefficient and channel's width/flow depth ratio, using a simplified expression for critical wavelength $L = D/(2C_f)$ [*Edwards and Smith*(2002)], where D is the mean depth of the flow. This open a possibility of calculating flow velocity directly from the stress balance equation $U = (gDS/C_f)^{1/2}$, where $g = 3.74$ m/s^2 is Martian gravity, and $S = 10^{-3} - 10^{-2}$ is the channel slope using only directly observable quantities, k and B; $U = (4gS/k)^{1/2}\, B^{1/2}$. Taking into account ranges of B and k, we estimate mean flow velocity to be $1 - 10$ m/s for outflow channels like Shalbatana, Dao, and Ma'adim Valles, and $0.6 - 6$ m/s for channels like Nirgal, Hrad, and Granicus Valles. Similarly, discharge can be expressed as $Q = (4/\beta)(4gS/k)^{1/2}B^{5/2}$, or

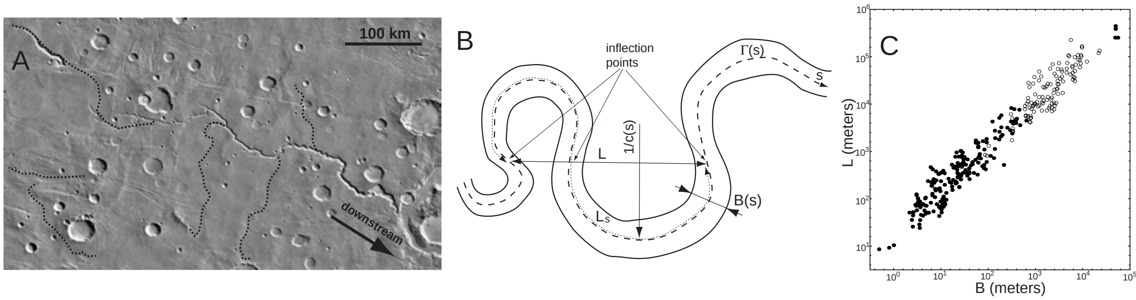

Figure 1: (A) Viking image of Nirgal Vallis showing a series of bends. The center of an image is at 311^{o}7E, -28^{o}76. The dotted lines indicate selected unchannelized paths of steepest descent. (B) Sketch to define terms used in describing character of a meandering channel. (C) Relation between meander width and its cartesian wavelength. Black dots indicate terrestrial meanders from a variety of different environments and the open circles indicate Martian meanders.

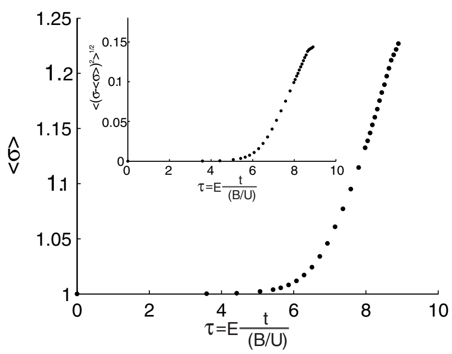

Figure 2: Evolution of average sinuosity and standard deviation of sinuosity (inlet) in a simulated channel as a function of rescaled dimensionless time τ. Simulation parameters are: $\beta = 30$, $\theta = 1.0$, $d_s = 0.005$.

$Q = (10^{-2} - 10^{-1})B^{5/2}$ m^3/s. This estimate yields values of discharge $10^7 - 10^8$ m^3/s for Shalbatana, Dao, and Ma'adim Valles, and $10^5 - 10^6$ m^3/s for Nirgal, Hrad, and Granicus Valles.

Martian meanders have low values of sinuosity, the range of σ is 1.09 to 1.6, with $\langle\sigma\rangle = 1.19$ and $\langle(\sigma - \langle\sigma\rangle)^2\rangle^{1/2} = 0.09$, pointing to their immature character. We have run simulations of channel evolution with parameters typical for terrestrial sand bed rivers because such parameters best reproduce wavelengths observed in Martian channels. Fig.2 shows a dependence of $\langle\sigma\rangle$ on τ – the rescaled dimensionless time. A unit of τ corresponds to $3 - 3 \times 10^2\ B_o^{1/2}$ yrs assuming typical terrestrial values of bank erodibility, E. The simulated channel reaches $\langle\sigma\rangle = 1.19$, a typical value of average sinuosity of Martian channels, at $\tau \approx 8$ indicating a typical period of fluvial activity of $10 - 10^3\ B^{1/2}$ yrs. However, this is a gross overestimation of the actual duration of the flow because, unlike a simulated channel, the real channel does not start from the straight line. Instead, the initial channel already possesses some sinuosity due to preexisting topography. We have developed a method to assess the sinuosity of an initial channel, $\langle\sigma\rangle_{int}$, from the average sinuosity of paths of steepest descent in the surrounding terrain. As an example, we estimate that a duration of the flow in Nirgal Vallis, is $\Delta\tau \approx 0.75$ or $\Delta t \approx 200$ yrs – a time needed to evolve the channel from $\langle\sigma\rangle_{int} = 1.16$ to present-day average sinuosity of Nirgal Vallis, $\langle\sigma\rangle_{pres} = 1.23$.

Discussion. Analysis of Martian meanders reveals existence of the wavelength/width scaling similar to an analogous scaling observed in terrestrial meanders. Since such scaling in terrestrial rivers is explained in terms of the bend instability model, we infer that the same mechanism operated on Mars. The independence of critical wavelength from the value of gravity explains why the same scaling is observed on the two planets. The existence of this scaling makes possible calculation of flow velocity from first principles using only directly observable quantities. This offers an alternative to a common practice of estimating U and Q from terrestrial empirical functions. Martian meanders have low values of $\langle\sigma\rangle$ pointing to their immature character. Furthermore, only portion of their sinuosity can be attributed to the action of meandering dynamics, other portion is due to preexisting topography. We submit that numerical simulations of channel evolution can be used to estimate flow duration. Our method offers an alternative to a common practice of estimating flow duration from the volume of excavated material, a method that requires values of unmeasurable quantities.

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