Solar coronal loops as toroidal plasmas stabilized by gravity*

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Coronal loops on the surface of the sun are the one of the most common visible manifestations of the structures in the solar interior. Loops contribute to the solar wind and strongly unstable ones can lead to large events such as coronal mass ejections that create the earth's space weather, making the understanding of loop dynamics of great practical as well as intellectual importance. Due to the difficulty of making solar observations, loop theories typically consider only the most important effects and no consistent steady state theory exists. This work models a loop as a segment of a magnetically confined toroidal plasma with both ends tied in the photosphere. It finds exact 3D solutions of the MHD force balance $\mathbf{J} \times \mathbf{B} - \nabla p - \rho g \hat{\mathrm{h}} = 0$ where g is the acceleration due to gravity, ρ the plasma mass density, and the solar vertical $\hat{\mathrm{h}} = \sin\phi \hat{\mathrm{R}} + \cos\phi \hat{\phi}$ in terms of the loop major radius R and toroidal angle ϕ. The MHD dimensionless gravity parameter $\hat{G} = ga/v_A^2$, where a is the loop minor radius, and v_A the loop shear Alfvén velocity, has steady state solutions at two powers $\hat{G} \sim \epsilon^2$ and ϵ^3 of the loop inverse aspect ratio $\epsilon = a/R_o$, depending on the plasma beta. In certain limits, the states reduce to known analytic equilibria for axisymmetric and helical fusion plasmas. The numbers match a range of typical coronal loops in the high beta limit $\beta \sim \epsilon$, where ϵ is typically a few percent. Since $\hat{G}$ is smaller at lower height for loops that grow by radial expansion, loops should naturally grow up to their stable height; very long loops may be metastable because gravity begins to decrease as $(R_{\mathrm{loop}} + R_\odot)^{-2}$ when the height approaches a fraction of the solar (photospheric) radius $R_\odot$. The gravitational steady states appear to be consistent with many observed properties of loops.

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