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Dynamos: Observation, Theory, and Experiment

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Astrophysical plasmas are often characterized by high magnetic Reynolds number, turbulent, flowing plasma in which the flow energy is continuously transformed into magnetic energy through the dynamo process. Understanding this energy transformation and predicting what form the magnetic field might take, be it small-scale turbulent magnetic fields or large scale magnetic flux is the dynamo problem. In this review, I will give an overview of the taxonomy of magnetic fields observed in nature, including those of stars, disks, galaxies and clusters of galaxies. Then, I will give an overview of the theory of dynamos based upon the relative values of the magnetic Reynolds number $Rm = VL/\eta$, the fluid Reynolds number $Rm = VL/\nu$ (or their ratio $Pm = Rm/Re$), and the scales at which magnetic energy grow. Both limits of Pm are relevant in astrophysics: diffuse plasmas have $Pm \gg 1$ whereas dense plasmas have $Pm \ll 1$. We also distinguish between fast and slow dynamos. Fast dynamos amplify magnetic field at a rate independent of magnetic diffusivity eta and probably require magnetic reconnection, while slow dynamos require resistive diffusion. Dynamos can be classified as small-scale or large-scale. Small-scale dynamos tend to generate magnetic energy but little net magnetic flux, whereas large-scale dynamos generate both net flux and energy. While the mechanism by which magnetic energy at small-scales is generated is now well understood, how a large scale field self-organizes from small-scale magnetic fluctuations clusters is a grand challenge for plasma astrophysics. Theoretical dynamos studies are now focused on understanding how subcritical transitions make some dynamos essentially non-linear and also how dynamos in nearly collisionless plasmas may differ from MHD dynamos. I will finish by reviewing how dynamo experiments have and may inform us about astrophysical dynamos.