Removing Stellar Activity from RVs Using Neural Networks

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Background

Exoplanet detection with precise radial velocity (RV) observations is currently limited by spurious RV signals introduced by the host star in the form of stellar activity (i.e. faculae, starspots). These stellar signals can mimic or hide the signals of exoplanets.

Here we show that a cross-disciplinary approach blending solar physics, exoplanet astronomy, and computer science can help us further our understanding of stellar activity. Using machine learning techniques such as linear regression and neural networks, we demonstrate that we can significantly reduce the RV scatter caused by activity signals for solar observations.

In the future, these or similar techniques could remove activity signals from observations of stars outside our solar system and eventually help detect habitable-zone Earth-mass exoplanets around Sun-like stars.

Methods

Radial Velocity (RV) method - exploits the gravitational pull a planet exerts on its host star which induces a radial velocity and red/blueshifts the starlight.

Convolutional Neural Networks (CNNs) - artificial intelligence algorithm that has revolutionized many complex tasks and is considered state-of-the art for shape recognition. CNNs require a training set.

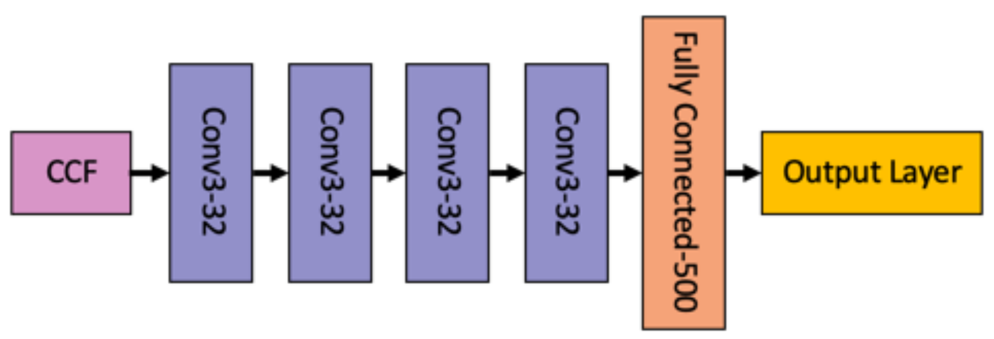

Figure 1: Convolutional Neural Network (CNN) Architecture- The architecture of our best-performing model. Conv stands for convolutional layers.

HARPS-N Solar Telescope – Our training set consists of 629 observations from the HARPS-N Solar Telescope spanning July 2015-2018. The HARPS-N spectrograph is a vacuum-enclosed cross-dispersed echelle spectrograph that has temperature and pressure stabilization.

Cross-Correlation Functions (CCFs) - As the host star moves away from us or towards us the average line spectrum is redshifted or blueshifted. We measure the average line profile by calculating the cross-correlation function (CCF) between the spectrum and a template of delta functions at the positions of the spectral lines. Besides radial velocities induced by planets, the shape of the CCF can also change based on stellar variability (Figure 1). We can train our neural network to recognize these shape changes in order to regress out stellar activity.

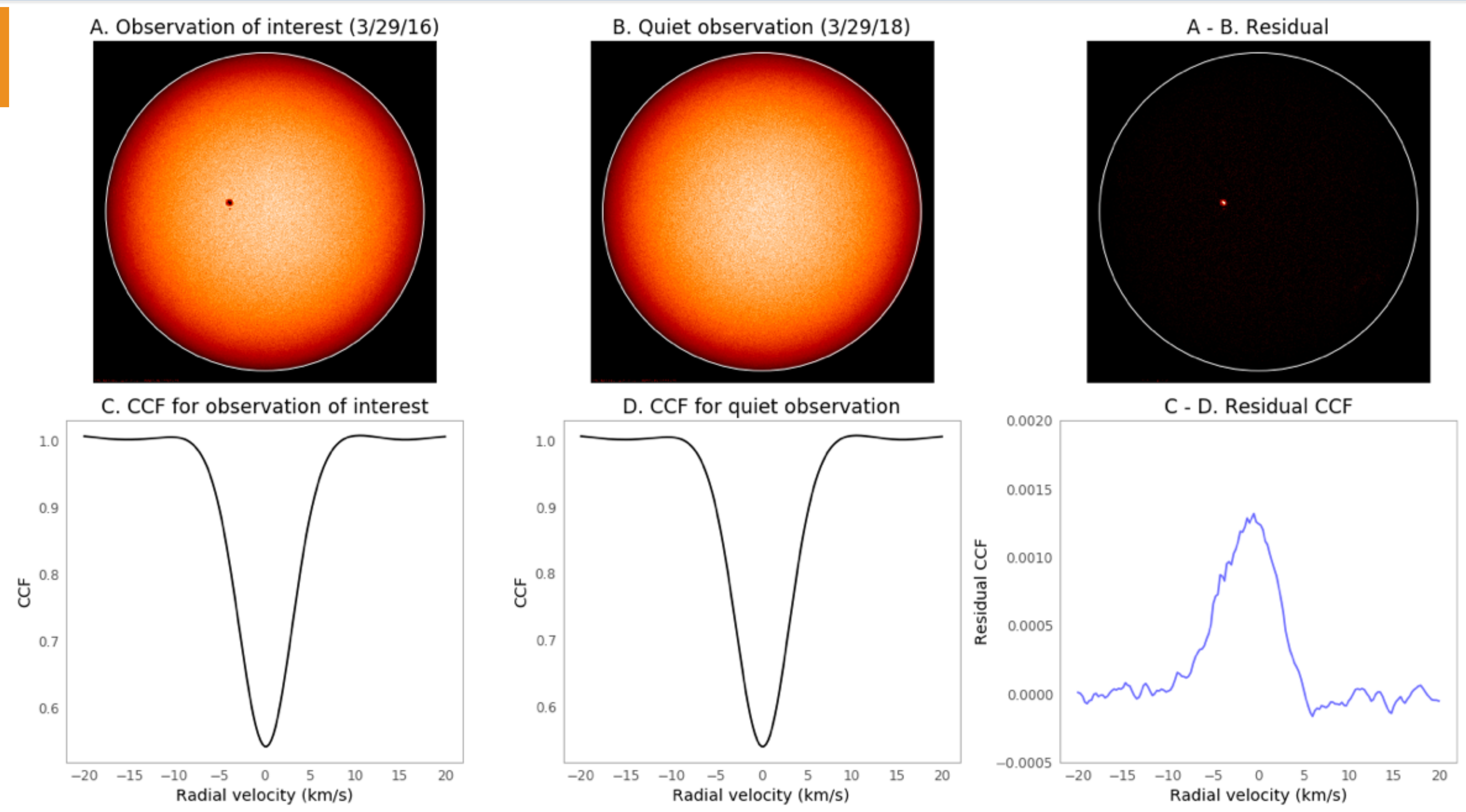

Figure 2: Residual CCFs– To highlight differences between CCFs, we subtract a quiet observation (B/D) from the observation of interest (A/C) to get the residuals (A-B/C-D).

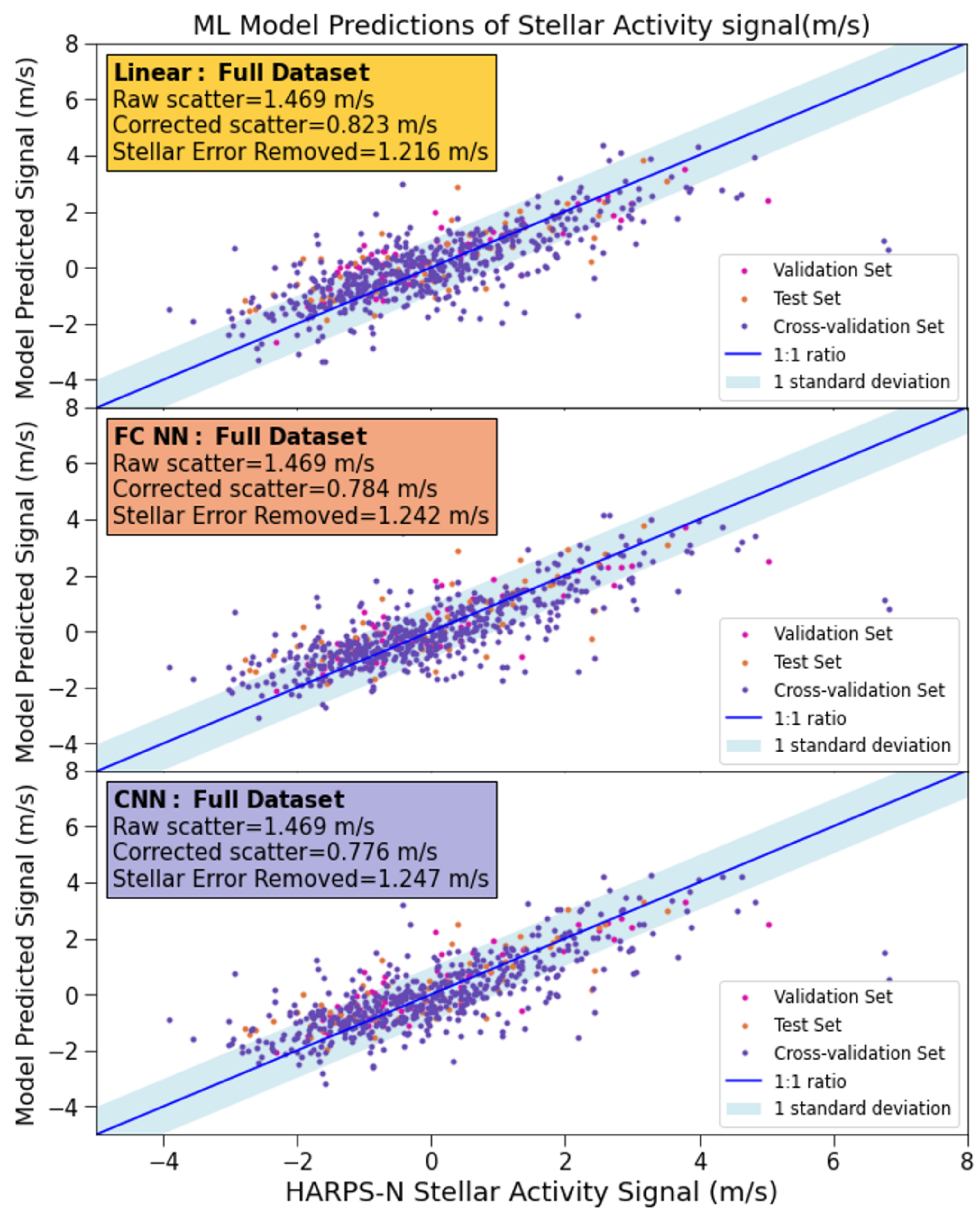

Figure 3: Convolutional Neural Network (CNN) predictions- Our CNN model can reduce the HARPS-N raw scatter from 1.5m/s to 0.737m/s by regressing out stellar activity signals based on the average line shape (CCF).

Results

- We find that these techniques predict and remove stellar activity from both simulated data (improving RV scatter from 82 to 3 cm/s) and real observations of the HARPS-N Solar Telescope (improving the RV scatter from 147 cm/s to 78 cm/s, a factor of ~ 1.9 improvement). Our results for HARPS-N Observations across all three architectures are summarized in Figure 3.
- We investigated the behavior of the raw and stellar activity corrected RVs in Fourier domain to see which signals are being removed to achieve this reduction in scatter (Fig. 4).

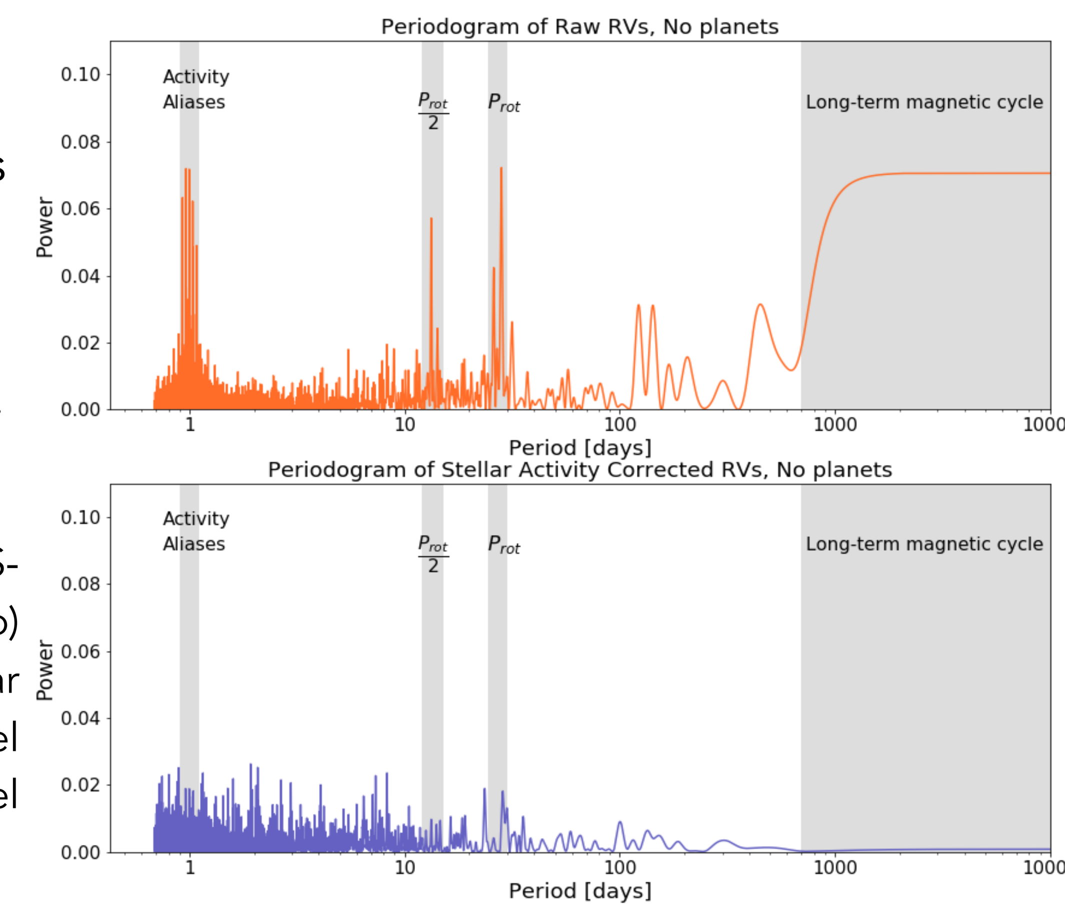

Figure 4: Periodiogram: HARPS-N Solar Raw (a) and Corrected (b) RVs in Fourier Space. The stellar activity peaks in the top panel dissapear in the bottom panel after applying our corrections.

Future Directions

- Continue modifying our method for extrasolar stars (See Figure 5 for a preview!).
- Further validate our method with HARPS-N Rocky Planet Targets and young planets orbiting young active stars

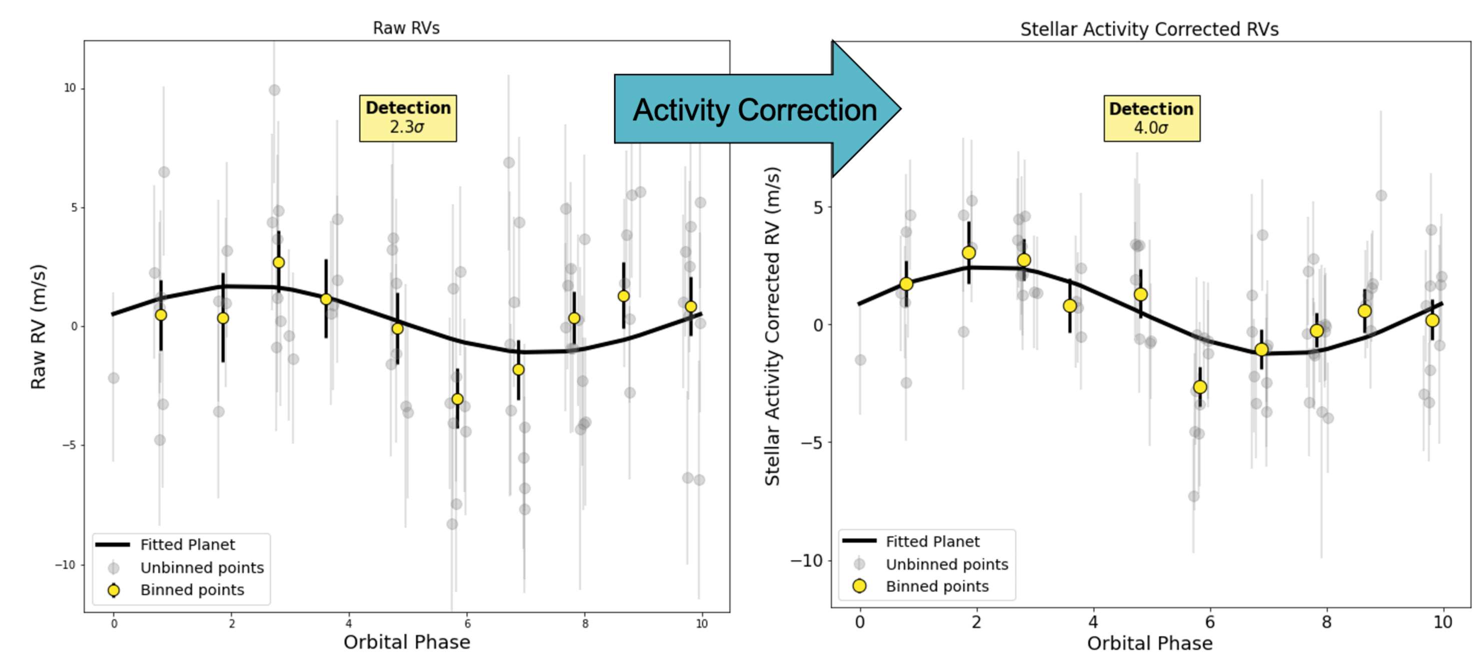

Figure 5: Work on applying our machine learning-based methods to a bright extrasolar star with a validated planet. This star has been observed with K2, TESS, and HARPS-N and has a confirmed period, but not a mass yet.

Acknowledgments

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References

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