High Resolution Observations of Sunspot Oscillation with BBSO/GST

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Outlines

1. Propagating modes of umbral running waves;
2. Penumbral running wave (PRW) driven by umbral oscillations;
3. Umbral oscillations likely also driven by PRWs;
BBSO/GST Observations

✓ NOAA 12127  2014/08/01  17:15-17:55  UT
✓ NOAA 12132  2014/08/05  16:19-17:19  UT
✓ NOAA 12731  2015/08/05  17:00-18:32  UT
✓ Hα:  6563 ± 1.0, ± 0.8, ± 0.6, ± 0.4, ± 0.2 and 0 Å
✓ FOV 70"x70"; 0.029"/pixel; cadence, 23s/30s;
✓ Phase-speed filter (Kaifan Ji) is used to obtain the filtered Hα images (mainly at Hα-0.4 Å) to see running waves.

\[
\begin{align*}
 f^{\text{low}}(v, v_{c1}) &= \frac{1}{1 + [v/v_{c1}]^{2n}}, \quad v_{c1} = 14 \text{ km/s} \\
 f^{\text{high}}(v, v_{c2}) &= \frac{1}{1 + [v_{c2}/v]^{2n}}, \quad v_{c2} = 4 \text{ km/s} \\
 f^{\text{low}}(v, v_{c1}) \ast f^{\text{high}}(v, v_{c2})
\end{align*}
\]
Sych & Nakariokov (2014) first found the umbral wave-front with an evolving two-armed spiral.

Our observations: in a decaying sunspot, the umbral wave-front has a one-armed spiral; in a matured sunspot, the wave-front has a two- or three-armed spiral.

**Velocity features:** they transversely propagate in both azimuth and radial directions, making rotating and radial expanding motions;

**Model diagnostic:** monolithic/spaghetti sunspot model (Cowling 1953; Parker 1979)
2. Penumbral running wave driven by umbral oscillations (Su et al. 2016a; Priya et al. 2018)

Lites et al. (1988) proposed that PRWs are driven by the umbral oscillations or the umbral and penumbral oscillations share a common physical basis. If so, why do they have different periods (3/5 min)?
At 17:39:28 UT, a part of wave-front was running across umbral-penumbral (UP) boundary as shown by red dots; 23s later, the next wave-front appeared as shown by yellow dots. Then, it propagated clockwise and expanded towards UP boundary; At 17:41:23 UT, a full helical PRW wave-front formed. It was produced by two umbral oscillations. It means that two or more oscillations may often generate one PRW.
3. Umbral oscillations likely also driven by PRWs (Priya et al. 2018)

Redshift ridges seen in the time–distance plots of velocity often merge, forming a fork-like pattern (Chae et al. 2014).

(Chae et al. 2014)

There are running waves propagating back to the umbra.
The stripes below red line inclined to the left, which seem having connection with the stripes above the red line. At the beginnings of umbral oscillation, there are always PRWs propagating back to umbra.
It means oscillations are excited closely related to PRWs.

- At the UP-boundary, some fragments of wave-front separate from a PRW;
- They coherently run back towards umbral center;
- There, they join together and then expand again. A new oscillation is born.

Event of 18:31:25 UT

Event of 18:34:05 UT

Hα-0.4 Å filtered images
4. Source of the quasi-period jets above light bridges (Liu et al. in preparation)

The surge activity above light bridges (LBs) has two components: one related to the magnetoacoustic waves, and the other to magnetic reconnection (Tian et al. 2018).

It seems that the jet comes from the right-side umbra (not itself).
4. Source of the quasi-period jets above light bridges (Liu et al. in preparation)

The jets above LBs are likely related to the jets from the umbra.
4. Source of the quasi-period jets above light bridges (Liu et al. in preparation)

Jets are related to umbral oscillations, but 6 times of oscillation correspond to 5 jets.

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5 times of oscillation correspond to 4 jets.
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Few jets are related to the brightenings of their footpoint.
4. Source of the quasi-period jets above light bridges (Liu et al. in preparation)

The fast jets have no periodicity at all.
4. Where do the quasi-period jet s above light bridges originate from?

**Estimation of jets’ acceleration by oscillations**

Velocity of the jets changes from $v_1 = 0$ to $v_2$. If the amplitude of oscillations is $v$, then we may obtain

$$\delta v = v_2 \sim \frac{v}{2}.$$  

That is, the jets’ final velocity is half of the amplitude, e.g., if $v = 5 \text{ km/s}$, then $v_2 = 2.5 \text{ km/s}$.

The oscillations are only a weak disturbance to the fast jets and they will show no obvious periodicity.
Conclusions

✓ The umbral wave-font has 1-3 armed spiral and it propagates both in azimuth and radial direction;
✓ Two or more times of umbral oscillations may often drive one PRW;
✓ Excitation of umbral oscillations may be related to PRWs;
✓ The quasi-period jets above LBs may originate from umbrae.